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Review

Our evolving understanding of aeolian bedforms, based on observation of dunes on different worlds

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ABSTRACT

Dunes, dune fields, and ripples are unique and useful records of the interaction between wind and granular materials – finding such features on a planetary surface immediately suggests certain information about climate and surface conditions (at least during the dunes' formation and evolution). Additionally, studies of dune characteristics under non-Earth conditions allow for "tests" of aeolian process models based primarily on observations of terrestrial features and dynamics, and refinement of the models to include consideration of a wider range of environmental and planetary conditions. To-date, the planetary aeolian community has found and studied dune fields on Mars, Venus, and the Saturnian moon Titan. Additionally, we have observed candidate "aeolian bedforms" on Comet 67P/Churyumov-Gerasimenko, the Jovian moon Io, and – most recently – Pluto. In this paper, we hypothesize that the progression of investigations of aeolian bedforms and processes on a particular planetary body follows a consistent sequence – primarily set by the acquisition of data of particular types and resolutions, and by the maturation of knowledge about that planetary body. We define that sequence of generated knowledge and new questions (within seven investigation phases) and discuss examples from all of the studied bodies. The aim of such a sequence is to better define our past and current state of understanding about the aeolian bedforms of a particular body, to highlight the related assumptions that require re-analysis with data acquired during later investigations, and to use lessons learned from planetary and terrestrial aeolian studies to predict what types of investigations could be most fruitful in the future.

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1. Introduction

Over the past couple of centuries, explorers and scientists of terrestrial dune fields have shown that the interaction between wind and granular material results in regular geometries and rates of evolution. Field observations and studies have inspired modeling and experimental works that have aided in the interpretation of measurable ripples and dunes as proxy indicators of wind speed and direction(s), grain sizes and sources, and underlying topography. The study of such landforms has been greatly extended and advanced by observation of analogous features on other planetary bodies. The comparison of these extraterrestrial features with aeolian process models has increased our understanding of aeolian bedform evolution in both directions – observations of (potential) aeolian bedforms generate investigations into the wind regime and granulometrics of surface materials on a planetary body, and also enable refinement of bedform evolution models as hypotheses about dominant effects are "tested" outside of Earth-conditions.

In this paper, we will review how our understanding (or assumed understanding) of sand dunes and/or ripples on a planetary body, and the information those aeolian bedforms yield about planetary conditions and processes, has progressed on different bodies. We hypothesize that the progression of investigations of these types of aeolian bedforms on a particular planetary body follows a consistent sequence – primarily set by the acquisition of data of particular types and resolutions, and by the maturation of knowledge about that planetary body. Our aim is to define that progression so we can better constrain our level of knowledge about the aeolian bedforms of a particular body, highlight the gaps in our knowledge (i.e., our assumptions), and predict what type of future investigations could be most useful in addressing new questions and/or enabling improvement over an assumption.

In the interests of space and focus, most discussion (and cited literature) will focus on dunes and dune fields – i.e., the larger aeolian bedforms and thus usually the first seen on a planetary body. We do delve into ripples (and martian mega-ripples) in portions of the discussion, but primarily as features seen on dunes and that complement dune analysis; and we acknowledge that far more could be said about these smaller-scale bedforms and that studies of these bedforms on Mars have contributed much more towards our understanding of the aeolian environment and processes than is presented here. We also do not generally discuss other types of aeolian bedforms within this paper. In particular, we do not include discussion of Transverse Aeolian Ridges (TARs) on Mars as there is still much debate about their formation mechanism (perhaps as they are an example of a feature that does not have a good terrestrial analog?) (e.g., Bourke et al., 2003; Geissler and Wilgus, 2015; Zimbelman, 2010). It is likely, however, that one could trace advancements in our understanding of TARs or other aeolian features along a similar progression of ideas as is presented here for dunes, as all of these features are studied via similar observation types and their dynamics and morphologies tie into similar questions about atmospheric and surface conditions. We also consider only the observation and analysis of bedforms on the surface of a planet, not e.g., evidence of past bedforms recorded within sandstone stratigraphy (and thus, while dunes and ripples can also form due to the flow of other fluids, such as water, in this paper we focus on aeolian dunes). Thirdly, in discussing our evolution in thinking about aeolian bedforms and processes on other planets, we focus on observation-driven science advancements; we touch on but do not delve as deeply into the parallel lines of investigation focused on model development and validation, empirical studies, and (analog) terrestrial field work – investigations that feed into advancements within (and between) the Phases that we outline here. Finally, we recognize that we present only a sampling of relevant studies – we aimed for enough to map out advances in understanding, to justify our proposed framework, and to provide a starting ground for any reader interested in learning more on a more specific topic.

In defining the "progression" of understanding (Section 2), we focus on Mars, Venus, and the Saturnian moon Titan – all planetary bodies where aeolian bedforms have primarily been explored with remotely acquired data. We also will comment on recently discovered candidate "aeolian bedforms" on Comet 67P/Churyumov-Gerasimenko and possible dune-like landforms on Io and Pluto. Within each phase of investigation (Subsections 2.1–7), we aim to identify the type of observations generally needed and connect these to the primary knowledge, assumptions, and questions that result, and then lead into future investigations (summarized at the end of each section). Furthermore, we identify the typical investigations (outside of direct studies of the aeolian bedforms) that follow each gain in knowledge, to show how aeolian bedform studies contribute to the larger study of that planetary body.

Our proposed framework of phases, regarding investigation of aeolian bedforms on a planetary body, is summarized in Table 1. We again note that this framework is not meant to be fully comprehensive for aeolian dune studies. We also note that progression in investigations and understanding is not necessarily linear/sequential – for example, planetary missions are generally focused on objectives other than aeolian bedform investigations, so observation types can be acquired in a "mixed" order. Additionally, the advent of new missions, methods, or models can lead to renewed activity within "lower" phases along with advances into higher phases. Science questions also often end up circling back as an assumption becomes superseded by new information and derived products and assumptions must be re-thought. Thus, in addition to identifying typical assumptions associated with each Phase, we use that framework to identify some example areas of knowledge gaps

Table 1
Summary of the investigation phases.

	Phase of aeolian bedform study on a planetary body	Area of interest	Characteristic(s)/feature (s) of interest	Data needed to move to this phase (from an earlier phase)	Complementary science investigations
1	Recognition of dune(s)	Dune (possibly a dune field)	Dune morphology (i.e., recognizable, distinctive gross dune shape or crestline patterns within a field)	Images (visible, radar, spectral, etc.) with sufficient resolution to distinguish dune from non-dune surroundings, and to determine general dune field pattern (e.g., linear/ arcuate and isolated/repeated shapes, general crestline direction(s))	Knowledge of and about analog features (terrestrial or planetary)
2	Analysis of gross individual dune characteristics: e.g., morphology and composition	Dune	Dune morphology, characteristics of surface materials	Images (visible, radar, spectral, etc.) with sufficient resolution to identify/correlate with dune margin and/or crestline patterns (possibly same data as Phase 1)	Global/regional-scale climate models (specifically: wind speed, direction, and variation); Dune formation models
3	Pattern analysis of the dunes within a field, including variations due to e.g., sediment supply and wind variations	Dune field	Dune shapes throughout the field	Coverage (of images, see above) throughout dune field	Regional/local-scale climate models (specifically: wind); Regional/local-scale topography; Studies of non-aeolian dune-modifying processes (e.g., polar or surface crust forming processes and their effects on dune field pattern); Maps of other aeolian features around the dune field
4	Regional and global surveys and aggregate-analysis of dune characteristics; e.g., estimates of age or sand volumes, identification of large-scale sediment transport pathways, or identification/estimation of the effect of location-related non-aeolian processes	Regional or Global (i.e., multiple dune fields)	Dune field characteristics (including morphology of field and dunes within each field) and spatial distribution	At least regional coverage of images or (often coarser and/or less definitive) proxy data (e.g., thermal inertia)	Expansive composition maps for identification of potential sand sources; Maps of other aeolian features; Global or regional-scale climate models
5	Analysis of superposed bedforms on the dune (such as ripples) formed due to wind interaction with the dune	Dune	Within/on-dune features (e.g., ripples)	(Very) high-resolution images	Ripple formation models; High-resolution topography (dune); Very high resolution climate model (CFD) (specifically: wind)
6	Observation of activity on the dune, including non-aeolian activity	Dune	Smaller-scale evidence of change (e.g., ripple crestlines, dune margins)	Repeat images for seeing planform changes (e.g., movement of material); these images need sufficient resolution and temporal baseline for changes to be observable	Ripple and dune migration models; Studies of non-aeolian dune-modifying processes (e.g., polar or surface crust forming processes and their effects on slope/dune morphology)
7	Groundtruth data	Dune	All features and components of the dune, especially sand size/composition	In situ observations of the dune, sampling and analysis	In situ observations of potential sediment sources

or the types of typical assumptions and results that need re-evaluation when new data becomes available (Section 3.1).

We also discuss how modeling (Section 3.2) and terrestrial studies (Section 3.3) relate to planetary aeolian studies. In particular, we highlight lessons learned regarding our understanding of aeolian processes and their drivers, as well as in methodologies employed. These lessons translate (or could translate) to improved results within other areas of aeolian science.

2. The phases of investigation

2.1. Phase 1: Recognition of dune(s)

This first phase of aeolian study is focused on the occurrence of the *first observation of a dune* (or, more likely, a dune field). Such an observation has immediate geologic significance as aeolian bedforms – dunes and ripples – directly record an interaction between the atmosphere and surface: specifically, the movement of granular material due to wind. Furthermore, a dune or ripple is more than a pile of sand – it is a distinctive landform that requires certain conditions to organize, and that appears to evolve and move "as a unit" through the aggregation of the actual movement of individual grains of sand, onto and off of the dune. Specifically, the existence of an aeolian bedform implies:

- A sufficient supply of saltatable (sand) grains,
- a wind of sufficient velocity and consistency to move those grains, and
- a period of consistent wind blowing, long enough for the bedform to form and evolve.

(We now examine what each of those underlined terms imply about the planetary body's environment, focusing on the larger-scale dunes that are typically observed first. A more technical summary of the conceptual framework for dune field dynamics and how this is affected by the sediment state of a dune field – related to sediment supply, sediment availability, and transport capacity of the wind – is described within Kocurek and Lancaster (1999).)

A sufficient supply means much more than the volume of the dune – for most dunes to form and evolve, sand must be able to move onto and off of the dune (possible exceptions would be climbing dunes or other such features where the sand accumulates due to blockage). Barchans in particular are an inefficient dune shape due to sand leakage from the horns (Hersen, 2004). Thus, an important implication with the first recognition of a dune feature on a planetary body is that a process must exist that will yield a significant amount of sand (discussed in within an example in Phase 4). Depending on the body, that process may involve erosion of larger blocks (e.g., as is common on the Earth, rocks eroding

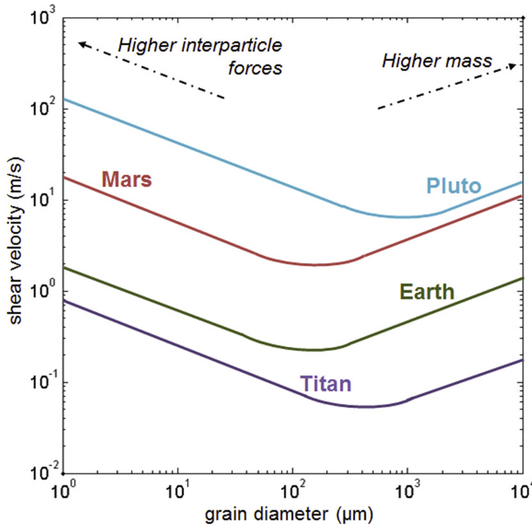

Fig. 1. Wind shear velocity needed to move grains of different sizes, on different planets. Plot showing the estimated threshold shear velocity for wind-driven transport of a grain of a specific diameter for (from top) Pluto, Mars, Earth, and Titan; curves are taken from Moore et al. (2015; Fig. 17). The general shape of the curve is reflective of smaller particles experiencing stronger interparticle forces (such as electrostatic forces), while larger particles have more mass – either effect thus requiring more shear velocity to initiate and sustain grain movement. The curve's minimum indicates the expected size of "sand grains" (i.e., the grains most easily lifted and moved by a shearing fluid – by saltation) on that planetary body, that would be involved in the formation of aeolian bedforms. On Earth, sand grains are commonly ~0.1 mm in diameter. On Mars observations of saltatable grains ("sand grains") in aeolian deposits such as dunes (e.g., Fig. 11) yield comparable diameters, which is consistent with the curves shown. The differences in shear velocity needed to initiate motion are due primarily to differences in the estimated air (fluid) and grain densities on each planetary body. The first investigations into these curves and how they shift under different planetary conditions (Greeley et al., 1974) were initiated based on observation of dunes on Mars (as described in the text: Belcher et al., 1971; McCauley et al., 1972; Cutts and Smith, 1973).

down to smaller grains) or a process that directly forms grains of that size. For instance, martian volcanic activity has been proposed to create sand-sized particles (Edgett and Lancaster, 1993; Wilson and Head, 1994) and photochemical processes in the Titan atmosphere may eventually lead to saltatable grains, perhaps via an intermediate evaporite or sedimentary location (Barnes et al., 2015; Radebaugh, 2013; Soderblom et al., 2007).

On the Earth, nearly all dunes and ripples are comprised of sand grains – and this refers to a specific size. (e.g., the Canada Dept. Agriculture (1976) lists sand as grains 0.05–2 mm in diameter). However, "sand grains" can also be defined based on dynamics. "Sand" is the size of grains most easily moved by a fluid (Bagnold, 1941) – smaller grains are held together by interparticle, cohesive forces and larger grains have more mass and so are held down more by gravity. Under the Earth's atmosphere and gravity, grains ~1 mm in diameter are able to saltate, and thus are the most easily moved by the wind. However, under the influence of a different atmospheric (or fluid) density and gravity, the grain size most easily moved by the wind could be a different size (Fig. 1; Edgett and Christensen, 1991; Greeley et al., 1974, 1980, 1992a; Moore et al., 2015). Throughout this discussion, when discussing "sand grains," we mean "the grain most easily moved by the wind (or fluid)" and not a fixed size range. Thus, the existence of a dune (i.e., a landform composed of sand grains) on a planetary surface yields a coupled constraint on the grains and the wind velocity.

Even if the wind reaches sufficient strength to transport sand, if it is not consistent (in direction and speed) over a sufficient period of time, the wind would just move small amounts of sand back-and-forth until that sand became trapped into depressions, sheltered areas, and other sand-traps; that sand would not be able to organize into a bedform. Models have shown that sand dunes have a minimum size (e.g., Claudin and Andreotti, 2006; Parteli et al., 2007); below this size the slipface is unable to develop. A slipface is necessary to capture sand on the sheltered, lee slope, which then allows the dune to continue growing and migrating.

To date, we have seen potential dunes on every deeply-studied body with an atmosphere and observable surface (including Titan, where dunes were considered unlikely: Lorenz et al., 1995), as well as a few bodies with no known atmosphere (Table 2). Based on the connections outlined above, this first "sighting" suggests the *accumulation of a lot of sand* (leading to questions about where the sand is coming from and why it is accumulating) and implications about *wind strength, direction, and consistency*. This yields a "groundtruth" observation for comparison with atmospheric models in both wind speed and direction (although it may be unclear when the bedform was created and thus what input conditions should be used for the model, or how the bedforms may have since been modified by non-aeolian processes).

Two classic examples of this are Mars and Titan. On Mars, signs of aeolian processes had been seen in cyclic, large-scale albedo changes and Mariner 6 imaged crescent-shaped features that were hypothesized to be very large barchan or parabolic dunes (Belcher et al., 1971). The first clear example of martian dunes was observed by Mariner 9 (McCauley et al., 1972; Cutts and Smith, 1973). Those observations suggested a wind regime that would allow for transport and collection of, as well as the presence of, a large amount of granular materials,[1] leading into laboratory studies of aeolian granular transport (Greeley et al., 1974, 1980). When Viking 2 imaged the north polar erg (Fig. 2), this led to investigations of martian erosional processes (acting on polar layered deposits or soils of lower latitudes?) and climate models (Cutts et al., 1976). (A summary of results from Viking and Mariner-based aeolian studies can be found in Greeley et al., 1992a.) On Titan, "cat-scratch" features had been observed circumnavigating its equator, but were not immediately recognized as dunes until the large draa of Saharan/Arabian/Namib deserts were brought to the attention of the Cassini radar team. The presence of dunes was a surprise as it had been hypothesized that while Titan's atmosphere may be capable of moving sand grains, it seemed unlikely that grains of the right size would exist (Lorenz et al., 1995). Observation of the dunes (Lorenz et al., 2006) led immediately to detailed investigations of what grains could be made of and how they would form – furthering studies of the chemistry on this Saturnian moon (Lorenz et al., 2006; Soderblom et al., 2007; Barnes et al., 2015), as well as leading to attempts to reconcile the observed dune morphologies with the model-predicted wind regime around the equator (Lorenz and Radebaugh, 2009).

Contrarily, while Venus has a dense atmosphere, *only* two potential dune fields and a few possible microdune fields have been identified within Magellan radar data (Greeley et al., 1992b, 1995; Weitz et al., 1994), which covers 98% of the surface with 100–200 m resolution (Pettengill et al., 1991) and shows wide coverage in other aeolian features such as windstreaks and potential yardangs (Greeley et al., 1995). This confirmed the hypothesis that aeolian bedform development on Venus must be limited, based on Venera 13 and 14 observations of the venusian surface that showed a dearth of aeolian ripples within loose material (Basilevsky et al., 1985; Florensky et al., 1983). (Note that for Venus, surface observations were first, before the mapping of sur-

[1] As Cutts and Smith (1973, p4151) put it: "The principal implication of dunes is a supply of noncohesive particles in the Martian surface environment and wind velocities sufficient for saltation transport. ... Dunes are not amenable to an alternative explanation of this sort. Thus we feel that we can now confidently assert the existence of a saltation regime on Mars", which leads to "many implications of a saltation regime such as wind abrasion, wind scour, and dust production."

Table 2
Recognition and first analysis of dunes and dune fields on planetary bodies (Phases 1–2), as presented in the literature.

Planet. body	"Aeolian" bedforms first sighted	Data used	Immediate Implications	Immediate Questions	References
Mars	Mariner 9, Hellespontus region of Mars, dense and large transverse dune field	Visual image of surface,<1 km/pixel	Dune material is dark (so some low albedo areas are regions of deposition, not erosion; and some dark material will saltate); Due to the lower atmospheric density on Mars, wind velocities may need to be much higher to move sand.	Which "dark splotch[s] or streak[s]" are due to deposition of material (vs. deflation of overlying bright material)? What is the source of the dark material? What velocity does this imply for the martian surface winds? Is high-velocity sand-blasting resulting in highly-efficient wind erosion?	Sagan et al. (1972)
		Above; comparisons to other albedo markings indicative of wind direction	Presence of lots of sand and saltation processes; Dune material accretion directions and influence of topography (craters) on field location and dune morphologies; comparable scale and shapes as terrestrial dunes	What is the composition of the sand? Why is it so dark?	Cutts and Smith (1973)
	Viking 2, north polar erg, transverse and barchan dune fields	Visual image of surface, 30–60 m/pixel	Lots of sand → some erosional process; Variability in wind regime; two wind directions in portions	What is the composition and source of sand? Why is it accumulated around the north polar cap?	Cutts et al. (1976)
			Strong winds; Two wind directions, thought to be seasonal; grains may be eroded from the northern plains	Are the dunes active, and how mature is the dune field? Are the dunes modified during the winter/early spring, when the entire region is covered by CO_2 ice?	Tsoar et al., 1979
Venus	Magellan, transverse dunes, two fields	Radar images, 75 m/pixel; compared with orientation of other aeolian features in same dataset	Lots of sand in specific areas → some erosional process (perhaps impacts?)	What is the composition and source of the sand? What are the saltation dynamics under a much denser atmosphere?	Greeley et al. (1992b)
Titan	Cassini, longitudinal dunes, large field around equator	Synthetic Aperture Radar images, 175 m/pixel	Lots of sand → some "grain" formation process; one dominant or at least two converging wind directions throughout equatorial region; pristine appearance and superposition over geologic features → young and possibly currently active	What is the composition and source of the sand? What is the underlying topography, causing accumulation in equatorial region and diversion of dunes? Is there any connection with the potential fluvial channels? Has the sand circumnavigated the globe several times (implying a lack of sand-sinks in the area)?	Lorenz et al. (2006)
		Visual and Infrared Mapping Spectrometer (VIMS) observations, 500 m/pixel	Observations of interdunes → recent activity and overall dune field maturity; spectral information → constraints on the composition of the dunes and interdune regions; photoclinometry yielded height and wavelength estimates	What information does the variability in dune coverage and height, and in the terrain that they cover, yield for the evolution history and conditions for these mature and recently active dunes? What are the dune grains made of, given their lower relative water ice content than Titan's average?	Barnes et al. (2008)
Comet 67P/Churyumov-Gerasimenko	Rosetta, moats, wind tails, and aeolian-like ridges/ripples	Optical imagery: OSIRIS orbiter camera images ($\geqslant$0.29 m/px), ROLIS decent camera images ($\geqslant$1 cm/px)	"Sustained" granular transport along the surface (so as to form aeolian bedform-like features) exists on a comet	How does granular transport work on a body without atmosphere? What is the moving agents? Are these bedforms accumulative or erosive? What is the grainsize of the bedform materials? What are the material sources? How long does it take to form bedforms?	Mottola et al. (2015), Thomas et al. (2015a,b)

face topography from orbit.) The implication was that venusian conditions and processes commonly obliterate features, the conditions for dune formation are not common on Venus (e.g., that there are few sands available on Venus or wind is not sustained at the surface), or that dunes are not generally visible via the radar images (Greeley and Arvidson, 1990; Weitz et al., 1994). Wind tunnel experiments (Greeley et al., 1984a,b; Marshall and Greeley, 1992; Williams and Greeley, 1994) and sand flux modeling (Kok et al., 2012) has shown that saltation under venusian conditions may occur in a very thin near-surface layer with very low velocity, which does not favor formation of large dunes. Thus, venusian sand transport appears more comparable to terrestrial bedform formation under water (Marshall and Greeley, 1992; Kok et al., 2012; Neakrase, 2015). Unfortunately, no new data about Venus has been acquired since Magellan, so Venus dune investigations remain stuck just past Phase 1 (with a small start within Phases 2–4, see discussion within Phase 2; Fig. 13).

Potential aeolian bedforms have also been seen on planetary bodies lacking an atmosphere. For example, planetary scientists were recently very surprised to see features that looked like aeolian bedforms (i.e. moats, wind tails, and dune-like ridges) on comet 67P/Churyumov-Gerasimenko (Fig. 3; Mottola et al., 2015; Thomas et al., 2015a,b). A comet seemed clearly to be a planetary body that would lack an atmosphere, and thus any wind – yet the features were observed. This immediately led to studies trying to determine how a "wind" could exist on this comet, if even tran-

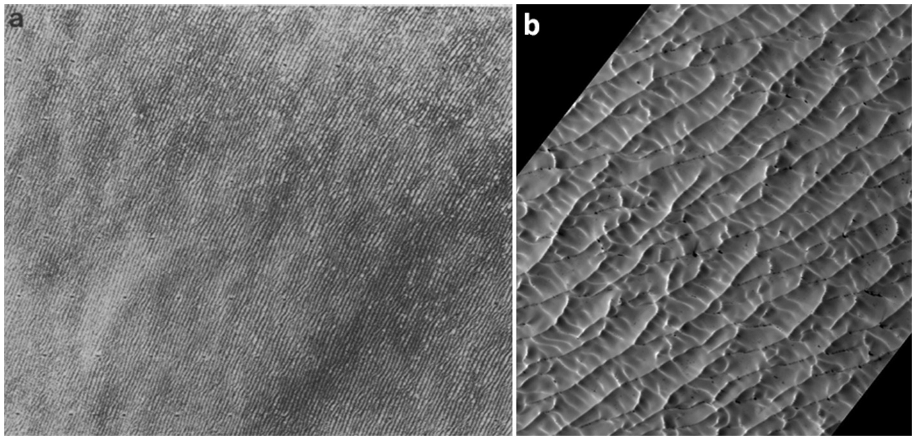

Fig. 2. An early image of the martian north polar erg. (a) These linear features, imaged near the martian north polar cap by Viking 2 (frame 59B32: 62 km × 104 km), were hypothesized to be dune fields based on their consistent orientation and wavelength, and low sinuosity, branching and merging. Image and description are taken from Cutts et al. (1976; Fig. 7). (b) Higher-resolution images have proven that these are dune fields, with a wavelength (between primary crestlines) of approximately 0.4 km. A few more orders of aeolian bedforms (e.g., the smaller crestlines, transverse to the primary crestlines) are also visible. Image is a portion of HiRISE PSP_007115_2600 (MRO/NASA/UA).

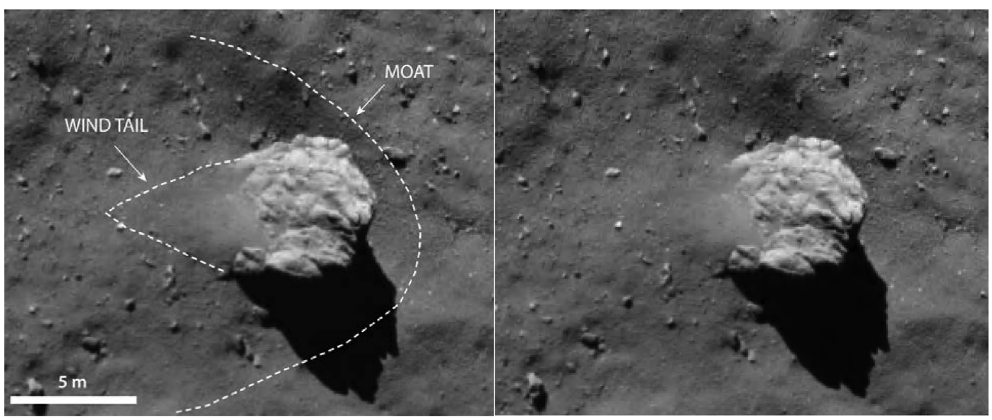

Fig. 3. A ~5 m boulder and potential aeolian features at Philae lander's touch-down-1 site. This ROLIS descent camera image shows a depression partly surrounding the boulder and a triangular-shaped apron on the opposite side have been interpreted as a moat and a windtail, indicating transport of granular material across the comet's surface (Mottola et al., 2015). Initial studies evaluated possible aeolian mechanisms for this transport. © ESA/Rosetta/Philae/ROLIS/DLR.

siently. One mechanism proposed to explain particle mobilization on comets was gas outflow from reservoirs of subsurface sublimating ice that emerges and erodes particles from channel walls (Cheng et al., 2013). However, since this process would only affect localized regions and the dune-like features on 67P have been observed in a much wider area, "splashing" initiated by airfall, i.e. ejection of particles by incoming projectiles, has been suggested as the most significant mechanism to explain particle mobility (Mottola et al., 2015; Thomas et al., 2015b). A three-dimensional cellular automaton model has proven that moats can result from abrasion of the surface by impinging particles, whereas wind tails develop where granular surface materials were shielded by obstacles from particle transport (Mottola et al., 2015). The results of this study put forward the explanation that the aeolian bedform-like features on comet 67P are of erosional nature, rather than depositional – but the questions and investigations that arose in response to the recognition of features that resembled aeolian bedforms were consistent with typical Phase 1 discussions.

The surface of Io is covered in a ubiquitous frost of SO_2 as seen by the Galileo Near Infrared Mapping Spectrometer (NIMS) (Carlson et al., 1992), likely mixed with dust and fine-grained materials, all ejected from the continuously erupting volcanic plumes and explosive volcanic eruptions (Kieffer et al., 2000; Milazzo et al., 2001). The surface as seen by the Imaging Science Subsystem (ISS) instrument on Galileo is mostly uniformly light-colored from this frost and generally smooth, with some fractures, slumps and pits (McEwen et al., 2000). In a few regions, there are landforms with dune-like characteristics: regular spacing, a slightly meandering form, "crestline" defects, and apparent topography visible through the uneven collection of frosts (not possible to confirm with Galileo's instruments). In one location, the dune-like landforms are found near a particularly active volcanic plume source, the Prometheus plume, which is sourced by advancing lava flows over vaporizing frosts (Fig. 4; Kieffer et al., 2000; Milazzo et al., 2001). It is possible this plume forms a localized atmosphere dense enough to loft particles from the surface and deposit them nearby in dunes, much like one of the processes hypothesized for forming the features on comet 67P.

The flyby of Pluto by New Horizons in July 2015 produced one of the most striking increases in image quality of a planetary surface in the history of planetary exploration (Moore et al., 2016; New Horizons, 2015; Stern et al., 2016). The landscape imaged during the flyby revealed a surprising diversity of landforms, which suggest varied geological and geomorphological processes active within recent geological history surface (Moore et al., 2016; Stern et al., 2016; Trilling, 2016). Mountains, glaciers,

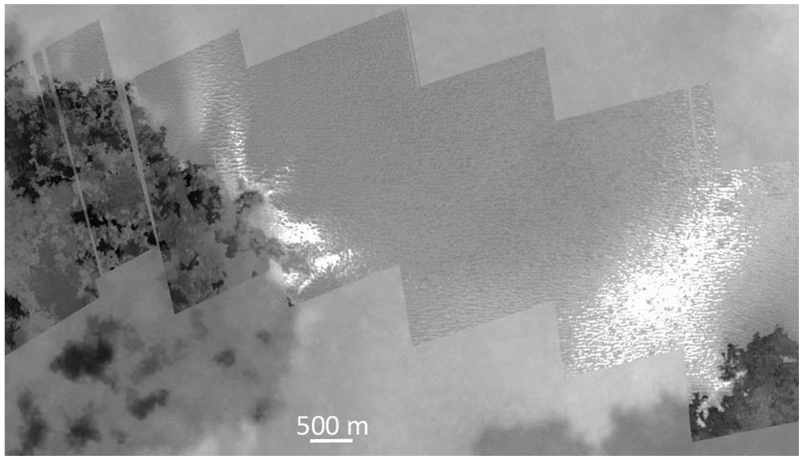

Fig. 4. Potential aeolian bedforms on Io. This ridged terrain has been postulated as potential aeolian bedforms, formed from volcanic plume deposits. Lava is erupting from a fissure about 40 km east (right) of the edge of this mosaic, and the 100 km tall Prometheus plume is erupting from somewhere near the western (left) end of this mosaic. The bright streaks radiating from the area where the lava flows (the dark features) overrun the field are where the hot lava recently vaporized the sulfur dioxide, which then recondensed on the lava-facing sides of the ridges. These images were taken by Galileo during a flyby of Io on February 22, 2000, with a resolution of 12 m/pixel. Image and description are taken from NASA Photojournal PIA02568.

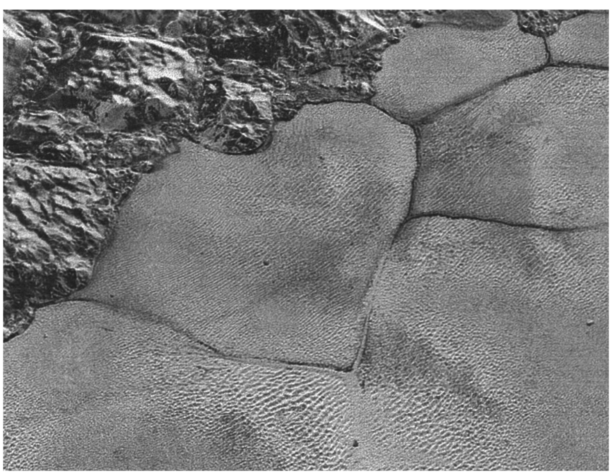

Fig. 5. Possible Pluto aeolian bedforms at the margins of the nitrogen ice of Sputnik Planum. These features are oriented approximately parallel to the 'shore' where the ice abuts mountains. Image width is approximately 75 km. Image credit: NASA/JHUAPL/SwRI.

plains, possible cryovolcanism and a surprisingly low density of craters covered much of the surface. Initial science results from the flyby noted the possible existence of 'windstreaks' (Stern et al. 2016) on Sputnik Planum, apparently extending in the lee of dark hills protruding through the nitrogen ice of which the plains are composed. Aeolian bedforms were speculated on before New Horizons arrived (Moore et al., 2015), and dunes have since been posited in the Baré Montes and enigmatic features in the Tartarus Dorsa have been interpreted variously as dunes or erosional aeolian features (Fenton, 2016; New Horizons, 2016). However, recent imagery from Sputnik Planum (Fig. 5) provides perhaps some of the most convincing examples of potential aeolian bedforms, with continuous linear features with a spacing of ~400–600 m. These features extend across the polygonal dark features, which have been interpreted as convectional cells within the ice, suggesting that they are the result of surface processes not related to the convective movement within the ice. Pluto is thus tentatively within Phase 1 of the progression, and if an aeolian origin can be shown to be feasible, then available data may be sufficient for progression into Phases 2–3. The dune-like landforms on comet 67P, Io and Pluto are well into Phase 1 discussions and primary work remains to be done for these features to determine their ultimate origin.

2.1.1. Summary of Phase 1

Data needed: Images of the surface topography, of sufficient resolution to identify the distinctive shapes of dunes – images could be visible or spectral imagery or radar scans of the planetary body's surface; identified analog (usually terrestrial) aeolian bedforms.

Knowledge gain (from that data): Existence of a potential aeolian bedform.

Assumptions generated: Conditions (wind conditions and grain size/supply) conducive to dune formation and evolution exist or have existed – note that this is a coupled constraint and further information is needed to estimate each individual measurement.

Questions: What is the composition of the grains? How were sand-sized grains formed? Why do the grains accumulation in that particular location (related to winds, topography, sand source)? Are the dunes active? If conditions are unusual (e.g., tenuous atmosphere), how does sustained saltation and/or reptation occur on this world?

Lead to investigations of: Models of surface processes and rates (chemical, erosional, etc.) that could create "sand" grains; Comparison to (global) atmospheric models; Independent measurements of surface conditions/composition for comparison to grain-formation models; Independent studies of wind speeds and/or grain sizes (e.g., thermal inertia) to decouple saltation conditions.

2.2. Phase 2: Analysis of gross individual dune characteristics

Analysis of the dune morphology (Phase 2) typically closely follows Phase 1, often via the same medium of an image of the surface. As models (e.g., Pelletier, 2009; Sauermann et al., 2001; Werner, 1995) and laboratory studies (e.g., Andreotti et al., 2006; Parteli et al., 2009) have established, a dune's overall shape and orientation yields additional information about wind conditions when the dunes were forming and evolving.[2] Thus, this investiga-

[2] However, establishing a connection between wind directions and dune slipface orientations sometimes is not a straightforward process – such studies often rely on many assumptions about timing of the winds and their consistency, and results are usually non-unique. Thus additional information is usually needed to evaluate a proposed interpretation. See Phase 3 for more discussion of the complexity that can be found in many dune fields.

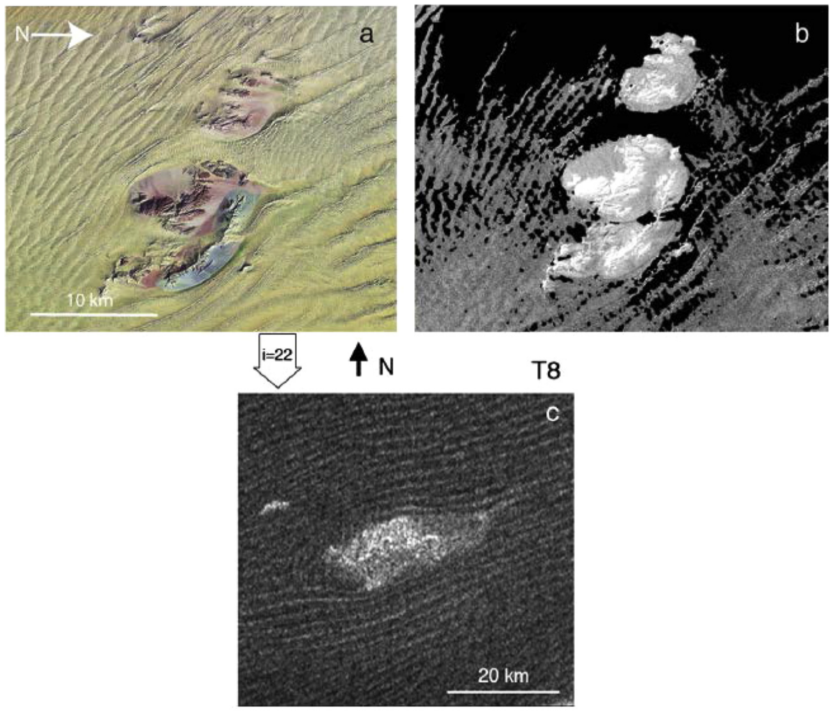

Fig. 6. Earth and Titan dunes, diverging around topographic obstacles. (a–b) Landsat 7 Enhanced Thematic Mapper Plus (ETM+) (Williams et al., 1998) and Shuttle Radar Topography Mission (SRTM) C-band (Uberblick, 2001) images of dunes in Namibia (centered on 25° 23′ S 15° 16′ E). The right image (b), a Synthetic Aperture Radar (SAR) image of the same dunes, shows bedrock as bright, because it is rough, and unorganized dune sands as dark, because dunes are smooth at the SAR wavelength of 6 cm (black areas are regions devoid of data returned to the SAR antenna). The winds blow southeast to northwest (bottom-left to upper-right), as evidenced by the dune-free regions in the lee of the bedrock topography and the diversion of dunes around the upwind sides of the topography. In the lower image (c), dunes similarly divert around topographic obstacles and resume on the downwind side, within this region of the Belet sand sea, Titan. This is a Cassini Radar image (300 m resolution) centered on 6.5° S, 251° W, with winds interpreted to blow southwest to northeast (again, bottom-left to upper-right). Images and description are from Radebaugh et al. (2010).

tion stage generally involves detailed mapping of dune shape (outline and crestline) and comparison to analog terrestrial dunes. Numerical models of sand transport and dune evolution are also used for comparison between dune-generated predicted wind directions and atmospheric models (possibly down to a mesoscale or regional scale and including the effects of large-scale topography).

For example, once it was recognized that the long, generally linear cat-scratch features on Titan were dunes (Lorenz et al., 2006), researchers began investigating what type of dunes were observed and what wind conditions were required for their formation and persistence (in addition to questions about what the sand may be made of). From the morphology of the dunes, visible in 350 m/px Synthetic Aperture Radar (SAR) data (Elachi et al., 2005) from the Cassini spacecraft (slightly hyper-resolution in nature in some locations because of the high contrast between SAR-absorbing sands and fractured, signal-scattering bedrock), it was determined they are longitudinal in type (also called linear; Lorenz et al., 2006; Radebaugh et al., 2008). Cassini Visual and Infrared Mapping Spectrometer (VIMS) data in select, high-resolution regions confirmed the general morphology of Titan's longitudinal dunes as well as their spectral contrast between sand and substrate (Barnes et al., 2008). On the Earth, longitudinal dunes are typically formed when several alternating winds of roughly equal transport strength (i.e., they move the same amount of sand) are >90° apart, yielding a single sand transport direction that is along the dune crestline (Fryberger and Dean, 1979; Parteli et al., 2009; Rubin and Hunter, 1987; Rubin and Ikeda, 1990; Tsoar, 1983). (An alternate hypothesis that had been put forth connecting longitudinal dune morphology and wind directionality for Titan and some Earth dunes is discussed in Subsection 3.2.)

Further information about these dune fields was then used to also predict the dominant wind directions, for comparison with climate models (discussed here, but merging into Phase 3 investigations). Titan's dunes are found strictly between 30°N and S, ringing the equator, and are oriented roughly parallel to the equator (Lorenz et al., 2006; Radebaugh et al., 2008). Their morphology, and especially behavior around topographic obstacles (wherein grains are piled up at the upwind margin and are more sparse at the downwind margin) indicated a general sand transport direction from west to east (Fig. 6; Courrech du Pont et al., 2014; Lorenz and Radebaugh, 2009; Lucas et al., 2014; Radebaugh et al., 2010). However, this was found to be at odds with the global atmospheric transport direction of east-to-west predicted in the equatorial zone by global climate models. Subsequent modeling studies revealed that seasonal or storm-driven winds could produce fast westerlies near the equator (Charnay et al., 2015; Tokano, 2010), possibly resolving this inconsistency.

On Mars, mapping of the duneforms observed by Mariner 9 (Masursky et al., 1972) and Viking orbiters (Snyder, 1977), combined with information about the surrounding surface topography and composition (including other potential aeolian features), was used to determine the wind direction(s) that would yield the dune crestline orientation(s), the wind and topography that would yield sand accumulation within that area and its likely stability (i.e., was this a stable sink for sand, or a temporary repository), and possible sand sources (Cutts and Smith, 1973; Greeley et al., 1992a; Thomas, 1981, 1982; Tsoar et al., 1979). For example, the large number of transverse dunes observed within southern mid-latitudes and north polar region on Mars (vs. longitudinal dunes) in Viking and Mariner images implied that dune fields were forming within regions of near unidirectional winds, and the asymmetry in dune field complexity between the north and south hemisphere was seen as evidence of a more complex southern wind regime (Greeley et al., 1992a; Thomas, 1981). After higher-resolution images became available and atmospheric modeling

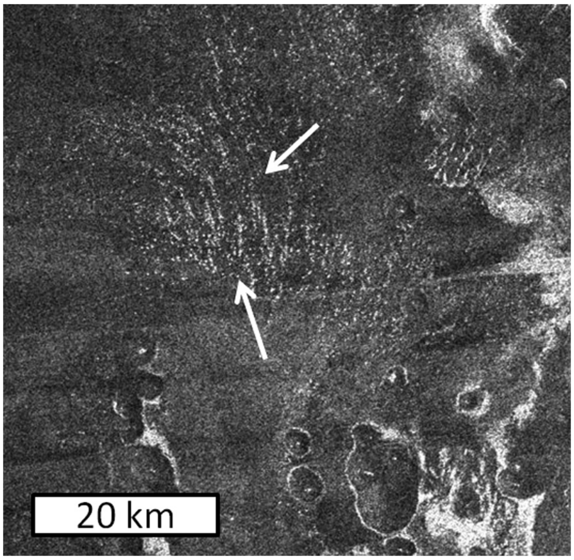

Fig. 7. Venusian dune field. This Magellan SAR image of the Aglaonice dune field (25° S, 340° E) shows a field of white dots that are interpreted as specular reflections from the slopes of transverse dunes (between the arrows). This type of reflection occurs if the slope is mostly smooth, and is oriented near-normal to the incidence angle of the radar (which is 35° or near the angle of repose); similar features are observed within Seasat and space shuttle radar images of terrestrial sand dunes. The implied wind direction of these features, based on their orientation, is also consistent with nearby bright and dark wind streaks extending from behind cones (not included in this cropped image). Radar illumination is from the left, and north is at the top. Image is from NASA Photojournal PIA00483, and description is from Photojournal and Weitz et al. (1994).

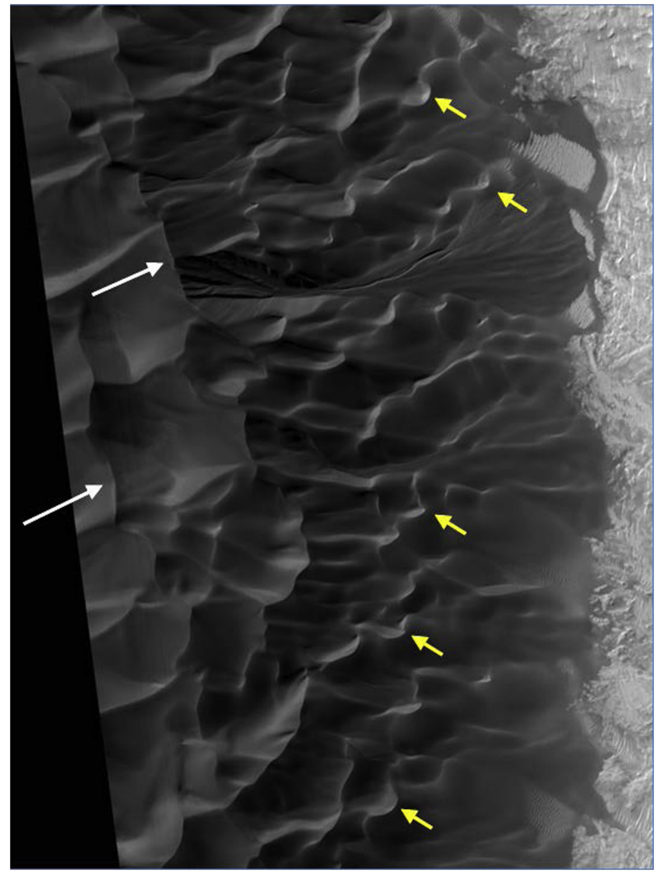

Fig. 8. The complex dune patterns found in along the eastern edge of Matara dune field, Mars (49.5° S, 34.8° E). This dune field, like many others in the Mars southern mid-latitudes, is a dense transverse dune field, captured within a crater. The transverse dune crestlines are oriented north-south with the clearest slipfaces towards the east (white arrows extend up the possible stoss slope, towards the dune brink). However, along the eastern side of this field, many smaller dunes (mostly barchans – yellow arrows, some possible transverse crestlines near the bottom of the image) are oriented with towards the northwest. This potentially reflects two periods (or just two timescales?) of dune evolution, with a change in the dominant wind direction. North is up and illumination is from the left. Image is a portion of HiRISE PSP_006648_1300 (MRO/NASA/UA).

became more refined in technique and topography/boundary inputs, a more detailed comparison was done to see if atmospheric models could reproduce the observed dune shapes and orientations. For example, mesoscale modeling of dunes within Proctor Crater on Mars based on Mars Orbital Camera Narrow Angle (MOC NA) (Malin et al., 1992) images matched two sets of dune slipface orientations (the primary and tertiary) to seasonal winds that were impacted by daily and seasonal insolation patterns and the crater topography, as predicted by a mesoscale model (Fenton et al., 2005; however, the secondary dune slipface orientation remained unexplained). This study validated the mesoscale atmospheric model by providing a reasonable explanation for the range of slipface orientations seen within that dune field, and thus advanced the use of these models within model-observation comparison studies for understanding aeolian processes on Mars.

Coupled with analysis of wind direction, observations of the dune's local surroundings can also be studied to identify sediment sources and sand transport pathways. In some areas, distinct sand transport pathways leading from the sediment layer to the dune bodies have been revealed by the detection of congruent material composition. For example, on Mars, local sediment sources for intra-crater dunes have been proposed at impact crater walls by comparative analyses of high resolution image and spectral data of dune bodies and the sediment layers exposed (e.g., Fenton, 2005; Geissler et al., 2013; Silvestro et al., 2010a; Tirsch et al., 2011). Within the Valles Marineris rift system, spectral analysis, morphological evidence of erosion and sand transport, and topographic information was used to show that diverse and distinct sediment sources serve as local and regional sources (Chojnacki et al., 2014).

On Venus, analysis of dune morphology is almost impossible due to lack of data. Dunes in both recognized dune fields are at the resolution limit of radar images obtained by Magellan mission (Fig. 7), the only adequate data source. Therefore, results of attempted of detailed analysis are not reliable and are controversial (Greeley et al., 1997; Lorenz, 2015). Modeling of anisotropic radar scattering (Kreslavsky and Vdovichenko, 1999) indicated that the microdune fields proposed by Weitz et al. (1994) possess abundant unresolved steep slipfaces.

In general, Phase 2-type investigations can continue for a long period with refinement of the investigations as higher-resolution images of the dunes are acquired, more information becomes available about the local topography and other evidence of aeolian processes and conditions, and/or atmospheric or bedform formation models are improved. This investigation phase may eventually grade into (and occur concurrently with) Phases 3 and 5 which involve, respectively, higher-resolution analysis of features within the dune field and features on the dunes formed by the dune-wind interaction (such as ripple patterns on the dune slopes). Additionally, as new observations, models, and analysis methods are developed, Phase 2 investigations can be renewed and revisited (as with all Phases beyond Phase 1).

2.2.1. Summary of Phase 2

Data needed: same as Phase 1.

Knowledge gain: Morphology of the potential crestlines and general dune shape; Composition of the dunes and surroundings; Possibly identification of local sand sources.

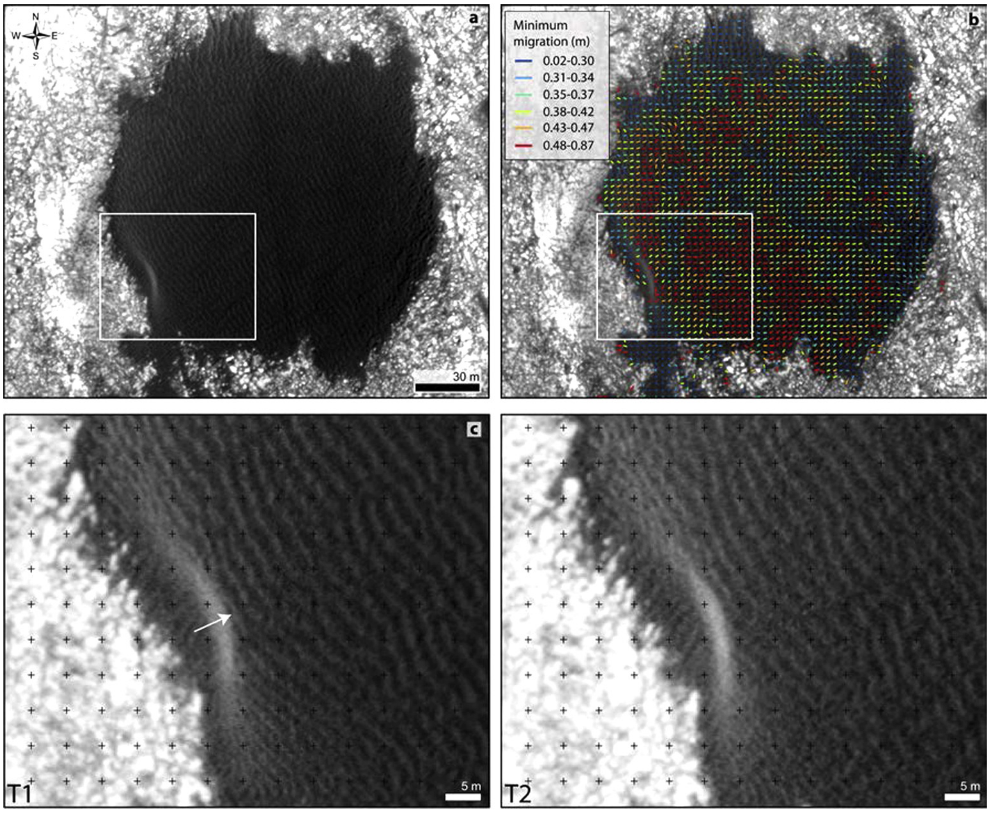

Fig. 9. Observed ripple movement on Mars. Images show (a) a rippled dome dune in the Bagnold dune field, Gale Crater, with (b) ripple migration over the dune stoss side between Mars years 28 (2006) and 29 (2008) (Silvestro et al., 2013). (c: T1–T2) The zoom-in shows one ripple (white arrow) moving over the dune brink, reflecting grain transport onto the slipface and suggesting that dune migration may also be occurring. HiRISE images shown: (a,c/T1) PSP_001488_1750 (taken 20 November 2006), (c/T2) PSP_009650_1755 (17 August 2008) (MRO/NASA/UA).

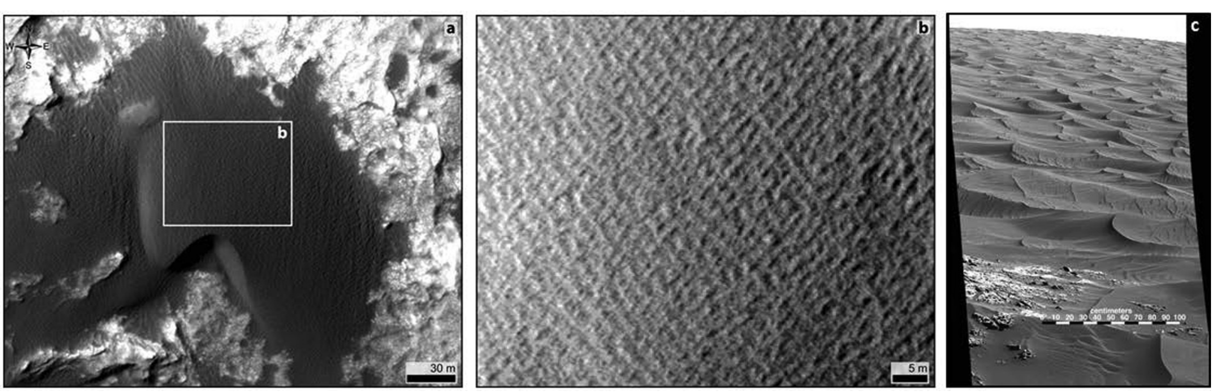

Fig. 10. Ripple morphology on Mars. (a–b) HiRISE images of High Dune, an active dune within the Bagnold dune field, Gale Crater, which has also been investigated by the MSL Curiosity rover (Bridges et al., 2016; Lapotre et al., 2016a). Visible in these orbital images is a complex ripple pattern on High dune's stoss slope, with what appears to be two sets of large ripples intersecting at right angles (Silvestro et al., 2016). This ripple configuration is typical of the Bagnold dunes and seems to be common on Mars. HiRISE images are: (a) ESP_042682_1755, (b) PSP_009294_1750. (MRO/NASA/UA) (c) This image of the High Dune stoss slope was taken by the Mast Camera on the MSL Curiosity rover, showing the complex morphology of these large ripples, which in this closer-inspection perhaps do not appear analogous to terrestrial sand ripples. The scalebar (one meter length) is for the lower portion of this cropped image. Image is from NASA Photojournal PIA20168.

Assumptions generated: Wind direction and consistency *hypothesized* to generate the observed shapes; Variations in wind speed implied by changes in sinuosity and shape through the dune field.

Questions: What sets the wind direction and causes its variations (e.g., daily or seasonal cycles)? Are these representative of present-day wind conditions, conditions during a past period, or a convolution of conditions during different past periods?

Lead to investigations of: Comparison of one to several dune fields with global/mesoscale atmosphere models; Reliably identify wind direction(s) implied by the dunes' forms.

2.3. Phase 3: Pattern analysis of the dunes within a field

Dune field evolution is related to the evolution of its constituent dunes, but occurs on a larger spatial and temporal scale and involves areas of investigation that are different from (and can be larger-than) the sum of its parts. For example, as dunes evolve within a field they exchange sand between each other through both sand flux and collisions, and environmental boundary conditions such as the sand influx geometry can affect dune field pattern development (Diniega et al., 2010a; Ewing and Kocurek, 2010). As

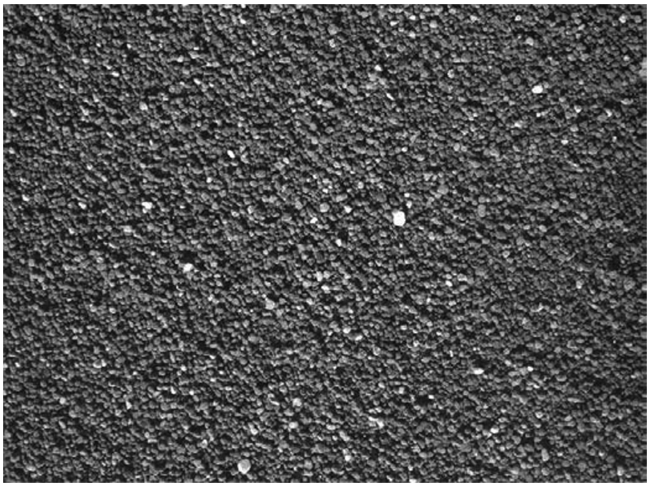

Fig. 11. Image of the undisturbed surface within the base of a martian sand dune called "High Dune" visited by the MSL Curiosity rover. The image covers an area 3.6 by 2.7 cm. Grain sizes show some range, but a fairly consistent size – comparable to dune sand on Earth. It was taken by the Mars Hand Lens Imager (MAHLI) camera on the MSL Curiosity rover's arm (Edgett et al., 2012) on Dec. 5, 2015. Image and description are from JPL (2015).

Fig. 12. An active dune slipface on Mars, imaged by NASA's Curiosity Mars rover. Multiple grain flows, slumps, and ripples are visible on the slipface of "Namib Dune," a dune within the "Bagnold Dunes" field along the northwestern flank of Mount Sharp, Gale Crater. None of these fine details are visible from orbital (HiRISE) images. The overall slope is 26–28°, and 4–5 m in height. This view combines multiple images from the telephoto-lens camera of the Mast Camera (Mastcam) (Bell et al., 2012), taken on Dec. 21, 2015. The scene is presented with a color adjustment that approximates white balancing, to resemble how the sand would appear under daytime lighting conditions on Earth. Image and description are from NASA Photojournal PIA20283.

such, it is necessary to model dune field evolution as more than just a collection of individually evolving dunes, and to recognize that the large-scale dune field pattern can reflect conditions (and changes in those conditions) around and throughout the field. For example, sand and dune influx conditions will be different near the upwind margin of the dune field than near the terminus or lateral margins (Ewing and Kocurek, 2010) due to proximity to sand sources or other dunes, or changes in topography or "cementing" influences (e.g., chemical duricrust or, on the Earth, vegetation) within the field (Kocurek and Ewing, 2005) (Fig. 6: examples of dune interactions with topography on Titan and Earth). Such changes can result in different dune sizes, spacing, or defect frequency (Diniega et al., 2010a; Ewing and Kocurek, 2010).

The effect of underlying topography is also a key parameter affecting dune characteristics at the dune field scale (Ewing and Kocurek, 2010). On Earth, bedrock topography has been linked to the effect of roughness variations induced by the dune field itself producing an internal boundary layer decreasing the shear stress downwind (Jerolmack et al., 2012) and/or to the feedback mechanism between long-wavelength topography and the dunes (Pelletier, 2015). The role of topography in enhancing and deflecting regional winds has also been invoked to explain complex dune field pattern on Mars in Olympia Undae (Ewing et al., 2010) and complex dune arrangements in Moreux (Cardinale et al., 2012) and Matara crater (Diniega et al., 2010b; Silvestro et al., 2012). However, it was only thanks to the availability of high resolution Digital Terrain Models (DTMs) based on High Resolution Imaging Science Experiment (HiRISE) stereoimages (Kirk et al., 2008) that the effect of underlying topography could be more precisely linked to different dune characteristics such as migration rates, dune heights, and density (Bridges et al., 2012b; Cardinale et al., 2016; Vaz et al., 2017). In particular, in Herschel crater dune density, slipface advancements and migration rates are all controlled by two major topographic highs on the crater floor (Vaz et al., 2017).

The dune field may also record changes in conditions over a longer-timescale than that recorded within any individual dune. Multiple patterns (e.g., different types of dunes) can be superimposed (creating a complex, versus a simple, dune field) as smaller dunes migrate and change in response to the new environment faster than larger dunes (Ewing and Kocurek, 2010; Hugenholtz and Barchyn, 2010; Kocurek and Ewing, 2005). We note that this possible complexity within dune fields can complicate analysis of the dune morphology (Phase 2). For example, even identification of the dominant (or most recent?) slipface orientations can be nontrivial. This is especially true within planetary dune fields where datasets may be limited to remote images, so dune slope angles and potential activity have to be interpreted from images of the dunes' planform appearance, possibly under suboptimal illumination conditions for this type of image analysis. For example, within the north polar erg on Mars, many dunes contain slipfaces pointing in opposite directions (sometimes on the same dune). One interpretation is that some of these fields may contain both active and fossil dunes (Gardin et al., 2012). Within the Mars southern mid-latitudes, at least two periods of dune-building (or dune-building occurring over 2 different timescales) are apparent as within the same field one can often find a dense collection of transverse dunes (with slipface towards the east) and then barchans clearly climbing up and over the transverse dunes on the east side (with slipfaces towards the west) (Fig. 8; Diniega et al., 2010b).

A lack of variations can also yield information about the field's and planetary body's history. On Titan, dune width and spacing measurements over >7000 linear dunes showed a high level of uniformity around the moon, with no signs of compound or complex dunes (Savage et al., 2014). This, coupled with the dunes' large sizes, indicates that Titan's dunes are mature features that have evolved within consistent and stable environmental conditions over a long period of time.

2.3.1. Summary of Phase 3

Data needed: Observations of dunes fields, of sufficient spatial coverage and resolution to note changes in dune patterns through-

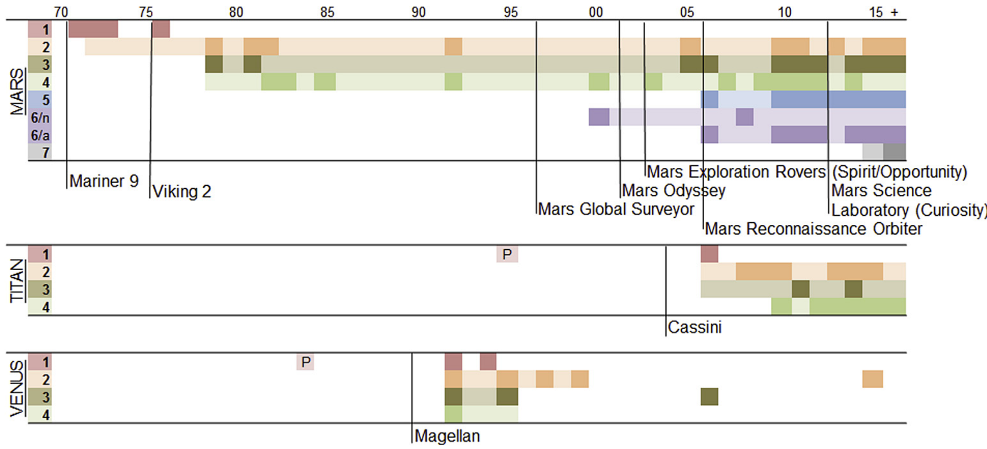

Fig. 13. Timelines showing movement into and through different investigation phases, for Mars, Titan, and Venus. Darker colors indicate publication dates for relevant studies (as referenced within this paper), and lighter colors indicate the general period of activity (again, based references within this paper and checked against google. scholar search results with keywords e.g., "Venus dunes"). Under Mars, Phase 6 is divided into observations of "no dune activity due to aeolian bedform processes" (6/n) and of such activity (6/a). Within Phase 1 for Titan and Venus, publications predicting a limit on aeolian bedform formation on those bodies are highlighted with a P – and the first observation of a bedform occurs later. Arrival dates of relevant spacecraft, to the planetary body, are included – for obvious reasons, these often initiate or re-invigorate investigations begun during a previous mission.

out the field, especially in tracing crestlines; Possibly need knowledge of topography.

Knowledge gain: The dune field pattern and shape; Maturity state (and possibly relative age) of the bedforms; Possible temporal changes in e.g., sediment supply and wind patterns.

Assumptions generated: Changes in the environmental conditions, in space or time.

Questions: For a given dune field, is sand sourced from one or several locations? Is the dune evolving through one dominant wind pattern, or several? Have the dominant effects (sand source or wind pattern) changed over the lifetime of the dune field?

Lead to investigations of: Explore influences on dune shapes beyond current dominant winds (*Phase 2*) – such as the location of sand source(s) or of sand-starved regions of the field, a transition between wind regimes, interactions between dunes (such as dune collisions), or other environmental influences/processes.

2.4. Phase 4: Regional and global surveys and aggregate-analysis of dune characteristics

As we gather information about dunes in more and more different dune fields around a planetary body, it becomes possible to aggregate data to deal with global, large timescale questions about aeolian processes and sediment supply, such as "How much sand is available in total?" and "Are there primary types/locations of sediment sources that can yield information about how that sand has been created, how it is transported, and whether it has been recycled?" Addressing such big-picture questions can provide important information for investigations of grain-producing processes (e.g., surface erosion) and planetary surface history over the lifetime of the involved sand grains. Note that while studies of grain history and sediment transport pathways involving terrestrial dunes may rely on detailed petrographic and heavy-mineral techniques, with geochronology (e.g., Garzanti et al., 2013), studies of planetary bodies often are based only on surface topography and, possibly, coarse compositional information.

For example, on Mars, an early near-global map of sediment deposits (including dunes) and wind streaks was used to generate first estimates of sediment transport pathways/source regions (Thomas, 1982). An early global map of aeolian features showed variations in time and space in the large-scale wind directions recorded by the orientation of dunes, wind streaks, yardangs, wind grooves, and deflation pits (Ward et al., 1985). Such studies have since been updated with increased coverage and image resolution (e.g., Hayward et al., 2007, 2014) and still provide important and often unique information about direction and variability in the wind patterns (down to intra-field scales), the influence of topography and local geology on wind-flow and bedform development, and likely sediment sources for the observed deposits. At a regional scale, the martian north polar erg volume has been estimated as ~1130–3250 km^3 of dark sand (Greeley et al., 1992a; Hayward, 2011), which is significant as the icy layers of the north polar cap has been proposed as the source of the circumpolar dune fields (Byrne and Murray, 2002; Tanaka et al., 2008). These deposits appear composed of recycled aeolian sediments, which were likely transported poleward and deposited (Breed et al., 1979; Byrne and Murray, 2002). This suggests that a huge volume of sand may have formed on Mars during an earlier epoch and that these sand grains have survived at least a couple of sustained dune-forming periods.

The Titan dune fields provide an example of how analysis of the distribution of dune field locations (on the planetary body, or relative position within regional topography) and morphologies (i.e., field outline or crestline patterns) can yield additional information about larger-scale atmospheric and topographic/surface conditions. Mapping of 16,000 Titan dune segments (covering 8% of Titan's surface which suggested that dunes cover a total of 20% of the global surface: Lorenz and Radebaugh, 2009) showed general dune field orientation and spacing patterns and confirmed that these features are within a global field with few longitudinal trends, but with latitudinal trends in orientation and limited to within 30° of Titan's equator. Although dunes on Titan are organized into several separate sand seas across the equator, all have some level of broad interconnectedness (Le Gall et al., 2012; Radebaugh, 2013; Savage et al., 2014). As such, studies of the Titan sand sources, sediment transport pathways, and deposition patterns are best analyzed from a "global" perspective.

Titan sands may be derived directly from the atmosphere, perhaps through clumping on the surface, though it is perhaps more likely the sand has been processed through erosion of organic sedimentary layers (Radebaugh, 2013), possibly close to the equator where fluvial channels have been imaged (Burr et al., 2013; Lorenz et al., 2008; Radebaugh et al., 2016). Other possible sources include erosion of the SAR-uniform mid-latitudes, a possible sedimentary deposit (Malaska et al., 2016), or the northern dry lakebed evaporite deposits, which the Visual and Infrared Mapping Spectrometer (VIMS) instrument has shown to have similar spectral characteristics (Barnes et al., 2015). Once the materials are transported into the Titan sand seas, they are incorporated into the giant linear dunes, and either stay confined to one sand sea or contribute to a global system of west-to-east sediment transport that persists over time (Savage et al., 2014). Topography appears to play an important role, as it does for sand seas on Earth, in that it can help confine the sands to certain regions or preclude them from others, like from the rugged Xanadu region (Lorenz et al., 2006; Radebaugh et al., 2011). Decreases in dune density within radar-bright and elevated regions may provide regional-scale constraints on Titan's winds for atmospheric models (Lucas et al., 2014). Furthermore, topographic obstacles can cause diversion of dunes and dune/topography relationships and perhaps reveal longer-term climatic changes (Ewing et al., 2015).

Consideration of the dune fields in aggregate can also allow for analyses that require a larger area or more numerous measurements to reflect larger-scale temporal or spatial trends. For example, dune fields on Mars appear very young as they lack craters, but constraints on their age had large uncertainties due to their low individual areal coverage. Adding the dune fields together allowed for a more robust estimated crater-retention age of $<10^4$ years (Fenton and Hayward, 2010). These dune fields also exhibit latitude-dependent morphological trends in crestline sharpness/pattern, dune slopes, and field shapes, so considering the dunes over the hemisphere enables studies of influence from polar as well as aeolian processes (Fenton and Hayward, 2010). Another study of southern intracrater dune fields on Mars compared dune field centroid locations, relative to the crater center, with mesoscale atmospheric modeling to look at broad-scale atmospheric trends (over a much longer time period than that recorded in dune slipface orientations within an individual dune field) (Hayward et al., 2009).

Although only two dune fields and a few microdune fields were identified with some certainty in the whole set of Magellan radar images of Venus, a few lines of indirect evidence suggest that unresolved small-scale anisotropic topographic features are ubiquitous; such features have been interpreted as unresolved gently sloping aeolian bedforms (Kreslavsky and Vdovichenko, 1999; Bondarenko et al., 2006). A comprehensive global inventory of aeolian bedforms on Venus will require global imaging data set(s) of a higher resolution than presently exists.

Beyond global imaging of the data-type first used to identify the dunes, proxy measurements can sometimes be used to supplement limited image coverage. For example, thermal inertia can be used to identify large deposits of unconsolidated, granular material. On Mars, further evidence that these dark patches with high-thermal inertia were aeolian deposits were that these were found downwind of topographic depressions (Christensen, 1983; Mellon et al., 2000). Thus global maps of thermal inertia with resolution ~100 m/pixel have been used to map dune fields around Mars and estimate the number of dune fields and their surface areal extent (Christensen et al., 2003; Hayward et al., 2007; Hayward, 2011).

2.4.1. Summary of Phase 4

Data needed: Identification of dunes around globe (from the data used in *Phases 1–3*, and possibly from proxy data such as thermal inertia).

Knowledge gain: Dune field location and (possibly) morphology/type distributions; Variations in location and morphology related to sediment supply, climate history, and/or and other active processes (e.g., related to latitude, regional topography); Identification of large-scale sediment transport pathways (larger-scale than field-specific results of *Phase 2 and 3*, and possibly first produced from low-resolution, but high-coverage datasets) based on global or mesoscale atmospheric models and observation of sediment sources.

Assumptions generated: Correlations between dunes and proxy data; Feasibility of extrapolation from studies of individual dune fields/sand sources to a global model.

Questions: How much sand is there, where is it from/stored, and how did it get there? Over what spatial and temporal scale is the sand being transported (i.e., what is the lifetime of a sand grain and is sand/bedforms being recycled)?

Lead to investigations of: Age estimation of dune fields (after aggregating land-areas to statistical significance; likely to be a relative or crater-retention age); Identification/investigation of large-scale sediment sources (locations and/or processes; perhaps updated from *Phase 2*); Global surface areal coverage of dunes/volume of sand.

2.5. Phase 5: Analysis of superposed bedforms on the dune formed due to wind interaction with the dune

Ripples, like dunes, form spontaneously within sand beds due to wind (or fluid) flow and record wind and sediment conditions through their period of formation and evolution. However, as these are much smaller features, they record conditions over smaller temporal and spatial scales and thus can be reflective of a different set of environmental conditions than dunes. To-date, ripple-like features have only been identified on Mars, where HiRISE images of the martian surface have resolution as fine as 0.25 m/pixel (McEwen et al., 2007) and in-situ observations have been acquired by the Mars Exploration Rovers (MER: Spirit and Opportunity) (Crisp et al., 2003) and the Mars Science Laboratory (MSL: Curiosity) (Grotzinger et al., 2012). These features have wavelengths of 1-to-a-few meters, have been found within sandy regions including on the slopes of dunes, and have been individually mapped and monitored for movement (Phase 6) (Fig. 9; Bridges et al., 2012a,b; Silvestro et al., 2011). The study of ripple morphologies and dynamics on Mars yields information about the wind flow over the dunes, under the influence of the local wind patterns as well as the dune topography. This yields information about the recent, local wind regime within several areas on Mars (Bridges et al., 2012b). Such information about the temporally and spatially small-scale surface wind dynamics can be compared with meso- and microscale climatic models and in-situ wind measurements (e.g., Jackson et al., 2015; Silvestro et al., 2013). In addition, because ripple morphology and migration rates are controlled by the topographic and wind flow boundary conditions imposed by the dune morphology (Kocurek and Ewing, 2012), studies of the ripples' form and variation can provide insights to the underlying dune's evolution (Ewing et al., 2010; Vaz et al., 2017).

Ripple mapping and monitoring have been an important tool within recent martian studies, where the crestline orientations and migration rates and directions of the large martian ripples are commonly used to reconstruct the wind regime over the dunes and to estimate sand fluxes (Ayoub et al., 2014; Bridges et al., 2012a,b; Cardinale et al., 2016; Silvestro et al., 2010b, 2011, 2013). Automatic approaches have been developed to derive ripple trend and migration rates, enabling high-resolution wind regime estimations and sand flux measurements to be computed over large areas (Ayoub et al., 2014; Bridges et al., 2012a,b; Silvestro et al., 2011; Vaz and Silvestro, 2014).

However, all of these studies have assumed that that the observed "smaller" bedforms on the dunes are analogous to terrestrial sand ripples, and that ripple trends and migrations are normal to the last wind of sufficient strength to move sand, as is typically the case for aeolian ripples on Earth. Recent work has drawn those assumptions into question:

- Most ripple patterns on Mars are dominated by sinuous crestlines (Lapotre et al., 2016a; Vaz et al., 2017), while on Earth ripple crestlines are typically straight (Rubin, 2012) (Fig. 9). In some areas, ripple patterns observed on Mars show complex arrangements with two crestlines intersecting at right angles (Fig. 10; Silvestro et al., 2011, 2013). This suggests that some of the ripples on Mars might not be in equilibrium with the last sand-moving winds or that the two sets of crestlines are contemporaneous, but oblique to the formative winds (Silvestro et al., 2016).
- Additionally, unusual longitudinal displacement of crest-line defect terminations and oblique crest migrations have been observed within orbital data in Gale and Herschel crater, suggesting that the large ripples of Mars are different from terrestrial impact ripples (Silvestro et al., 2016; Vaz et al., 2017). This hypothesis is in agreement with recent in situ observations from the MSL Curiosity rover, which shows that large ripples have sinuous and sharp crests and slipfaces with evident grainfall and grainflow structures (Bridges et al., 2016; Lapotre et al., 2016a) (Fig. 10) that are not common within terrestrial impact ripples. Superposing these large bedforms are smaller "terrestrial-like" impact ripples of ~ 10 cm in wavelength (Bridges et al., 2016; Lapotre et al., 2016a).

These observations suggest that terrestrial aeolian impact ripples might not be good analogs for the martian large ripples (Lapotre et al., 2016a; Silvestro et al., 2016; Vaz et al., 2017). As this gets worked out, previous studies will need to be carefully reviewed, such as where the interpretation has been that a multi-directional wind regime exists, perhaps triggered by the local dune topography or by larger topographic features (e.g., Jackson et al., 2015; Silvestro et al., 2011). Also, the presence of such large ripples on the dune's stoss side and their migration across the slipface (Figs. 9 and 10) may alter the wind profile above the dune and the slipface dynamics, beyond the way that these processes are typically captured in dune evolution models applied to terrestrial dunes and their ripples (e.g., Ewing et al., 2016). Increased coverage of high-resolution images coupled with in situ observations by rovers are necessary to progress understanding of the nature and dynamic of the martian large ripples. This is fundamental for understanding how these ripples can be used to constrain local wind directions and to tune sand flux estimations over the dunes.

2.5.1. Summary of Phase 5

Data needed: Higher-resolution images of dune field, reflecting variation over the dune, including in composition or granulometrics; Mapping and analysis of second-order and higher-order bedforms (e.g., ripples) and how these reflect the wind pattern around the dune.

Knowledge gain: Measurements of ripple movement and characteristics over the dune.

Assumptions generated: Use of the right analog features/models for interpretation of the smaller-scale features; Recent, local-scale wind-flow directions.

Questions: What is the local sand flux and wind patterns over the dunes (as reflected in ripple movement)? Are grains sorted within the ripples, and if so, why? Is ripple movement coupled with/connected with current dune evolution, or e.g. does ripple movement reflect a surficial mobile layer of sand over a relict dune core?

Lead to investigations of: Wind diversion around dune topography; Observation/better understanding of local source regions.

2.6. Phase 6: Observation of dune activity (aeolian or otherwise)

Only recently has it been observed that martian dunes and ripples are very actively migrating and evolving within the present-day climate (Fig. 9; Bourke et al., 2008; Bridges et al., 2012a,b; Chojnacki et al., 2011, 2015; Fenton, 2006; Geissler et al., 2013; Silvestro et al., 2010b, 2011, 2013). Previously, an incongruence appeared in our understanding of present-day martian sand transport, as the morphology of many aeolian bedforms (apparently sharp crestlines of dunes and ripples) and a surface observation of saltation (Greeley et al., 2006) and ripple movement (Sullivan et al., 2008) suggested that some aeolian bedforms should be active. However climate models did not produce the wind velocities predicted for saltation processes to occur under present conditions and no bedform motion was observed within higher-resolution images (although some dome dunes were seen to disappear (Bourke et al., 2008)). This was taken to imply that martian dunes may be stabilized (e.g., Zimbelman, 2000) and possibly relict features of a past climate with a denser atmosphere (e.g., Breed et al., 1979), and that surface degradation processes must be slow. However, acquisition of a sufficient temporal baseline and careful comparison of overlapping high-resolution images now yield measurable and consistent changes in dune margin and ripple crestline locations through several fields (e.g., Endeavor Crater: Chojnacki et al., 2015), and show that sand fluxes on Mars are comparable to sand fluxes in the Antarctic Dry Valleys (Bridges et al., 2012b). Within Endeavor Crater, these martian sand fluxes are sufficient for dune turnover times to be much less than the time since known large climatic shifts (e.g., an obliquity shift or increased atmosphere density), implying that these dunes are not records of paleo-climate conditions (Chojnacki et al., 2015).

These new observations, proving that sand is currently moving on Mars in large volumes and that at least some aeolian bedforms are presently active, were helpful in the advance of sediment flux models and understanding how sediment flux dynamics may vary on different planetary bodies. For example, an update to the model of steady state saltation (Kok and Renno, 2009) and application to Earth and Mars conditions (Kok, 2010) showed that saltation can be maintained on Mars by wind speeds an order of magnitude less than that required to initiate it, while nearly the same wind speed is needed to both initiate and maintain saltation on Earth. This provides a viable explanation for why aeolian bedforms appear to evolve at lower-than-predicted wind velocities (as well as an explanation for the smaller-than-expected minimum dune size on Mars (Kok, 2010)). Estimates of aeolian sand flux (in the present or past) are important as they feed into models of surface erosion rates (e.g., Golombek et al., 2006, 2014).

Sand dunes on Mars are also subject to other processes in the present-day. For example, alcove-apron and alcove-channel-apron (i.e., gully) formation has been observed in southern mid-latitude dune fields (Fig. 8; Diniega et al., 2010b; Dundas et al., 2012, 2015) and similar activity has been observed in the north polar dune fields (Hansen et al., 2011, 2015; Horgan and Bell, 2012), moving large volumes of sand downslope and possibly contributing to the overall migration of the dunes. Some have proposed that this activity may have aeolian drivers (Horgan and Bell, 2012; Treiman, 2003), but most studies have shown a seasonal control on the timing of feature formation and evolution, possibly related to CO_2 frost processes (Diniega et al., 2010b; Dundas et al., 2012, 2015; Hansen et al., 2011). It is also possible that both aeolian and seasonal frost processes have an influence on these types of dune modification activities (Hansen et al., 2015). Regardless of underlying process, these changes are actively modifying the dune slopes (Allen et al., 2016; Diniega et al., 2016; Hansen et al., 2011) and thus need to be investigated and explained to form a complete story for the martian dune evolution and accurate interpretation of observed dune morphology.

It is also important to note that some dunes have features indicative of a lack of activity, such as fissures on north polar dunes (Portyankina et al., 2012) and pits and softened topography on southern mid-latitude dunes (Fenton and Hayward, 2010). Such evidence for stability can provide constraints on the current availability of mobile material and the near-surface wind environment, as well as a contrast with the conditions when the (now inactive) bedform had evolved.

2.6.1. Summary of Phase 6

Data needed: Repeat images of sufficient spatial and temporal resolution to detect (and measure) changes in surface morphology (or lack thereof).

Knowledge gain: Observation and constraints on the estimated (average/net) amount of sediment transport.

Assumptions generated: Activity rates observed in the present-day can be extrapolated to past times and conditions.

Questions: What other processes are contributing to dune evolution? How much sediment is moving within the present climate? Has that amount of aeolian sediment transport changed since a previous climate?

Lead to investigations of: How the estimated sediment transport may affect surface erosion rates (including formation of sand) and formation of other aeolian features such as yardangs; How the climate has shifted, if changes in sediment transport are apparent.

2.7. Phase 7: Groundtruth measurements

To-date, we have only visited – at ground-level and up-close – dunes on one planet other than the Earth. While various Mars rovers have in situ imaged sand deposits and ripples (e.g., Greeley et al., 2006; JPL, 2012, 2014; Sullivan et al., 2005), the MSL Curiosity rover's visit to Bagnold Dune Field is the first in situ observation of dunes and dune sand (JPL, 2015; Bridges et al., 2016). This rover has examined dune sand on several different slopes on and around dune thought to be undergoing different levels of aeolian activity (based on orbital observations of ripple migration and the strength of spectral signatures of dust cover (Lapotre et al., 2016b)). Within even the first observations of dune sand (scooped from the stoss slope and imaged on the lee slope; Fig. 11), grain size differences have been noted that are perhaps correlated with differences in grain composition (as grains of different sizes appear to correspond to different materials) (Achilles et al., 2016; Cousin et al., 2016; Ehlmann et al., 2016; Pan and Rogers, 2016). Images of the lee slope of the more active "High dune" have yielded many grainflow features and potentially evidence of some level of induration (Fig. 12; Ewing et al., 2016) – none of which were visible in the orbital images. The first results of this work are currently being put together, and we look forward to learning more about the first in situ investigated extraterrestrial dunes.

2.7.1. Summary of Phase 7

Data needed: In situ observations of the dune and dune sand (possibly from different portions of the dune); Possibly observations of saltation on the dune or grainflow on the slipface.

Knowledge gain: Size, composition, and other characteristics of grains involved in saltation.

Assumptions generated: That the observed characteristics and activity are not anomalous, in time and space (i.e., the observation didn't catch a rare circumstance/event).

Questions: Why do the grains look as they do, and what causes the variation/distribution in grain size? How representative is this observed dune's characteristics and activity? What causes the dune's features? How can observations of sediment grain size and bedform morphology provide insight regarding transport processes and the nature/frequency of mobilization events?

Lead to investigations of: Models of dune activity and evolution, and generation of the observed sand grains (extending or perhaps redirecting previous work); Based on in situ observation of features that may not be visible from orbit, revisiting implications about dune activity and characteristics and how information feeds back into models of dune evolution.

3. Discussion

There are some differences between the aeolian science investigations undertaken on each planetary body – in particular as study methods of more recently studied bodies can build from lessons learned in aeolian bedform studies of a previously observed body, and as overall our understanding of aeolian processes becomes more refined as models are forced to reconcile with a wider range of environmental and planetary conditions. But, as has been described, studies of aeolian bedforms on planets (other than Earth) broadly tend to follow a similar pattern of gained knowledge, generated assumptions, and follow-up investigations (that rely on the new knowledge and assumptions). The similarities in the history of aeolian science over different planetary bodies (Fig. 13) are due partially to the knowledge-advancement at each body being based on the same types of data. Such data is usually acquired in the same order, which is based on the way in which higher-resolution and increased coverage are acquired during extended or subsequent missions, and as concepts and investigations mature and become more specific within all areas of planetary exploration.

Within that progression, we focus here on the gaps that seem likely to occur for any planetary body. We then move beyond planetary aeolian studies, to look at the interplay of planetary aeolian bedform studies with investigative fields that follow their own sequences of discovery and refinement: aeolian process modeling and terrestrial aeolian studies.

3.1. Gaps that can form within the planetary aeolian science sequence of investigations

Over time and as more data is acquired, our understanding of aeolian processes and interpretation of the aeolian landforms builds. However, as that understanding builds, it is important to keep track of which building blocks are assumptions and not actual observations. It is necessary for assumptions to be made to keep the science investigations moving forward and to guide development of the next set of investigations, but an assumption that is treated like an "observation" can lead to models with unrecognized limitations, which in turn can lead to incorrect interpretations of new observations or even a lack of attention paid to "contradictory" observations. Thus, assumptions should be recognized as such (and not treated as data) and be re-evaluated for consistency with new and different data, until direct measurement of the assumed variable or process is possible – doing this can make it easier to identify and investigate intriguing new understandings about processes and conditions.

Several examples of areas where new information has supplanted previous assumptions have been mentioned within the discussion of the investigation phases (Subsections 2.1–7). Some additional examples:

- As higher-resolution and more detailed studies are completed about specific dune fields, results of these studies (Phases 5–7) should be inserted into field (Phases 2 & 3) and global studies (Phase 4) that previously relied on lower-resolution or less complete data and assumptions about form and process uniformity (in time and space) through the field. As was discussed under Phase 7, the martian large ripples are a new example of this – where in situ observations are drawing into question previous work done regarding the scaling of aeolian bedform size between Earth and Mars and interpretations of ripple crestline complexity, that had been based on interpretation of orbital images. In general, as more detailed studies are conducted over specific dune fields, it is important to regularly consider how those results fit (or not) within the results of larger-scale studies.

- These observations have also led into a model of a potential new mode of subaerial bedform migration and evolution (Lapotre et al., 2016a). As discussed in Phase 5, on the stoss slope of Namib dune, two types of ripples have been imaged: the large ripples (few m-wavelength) were previously observed in orbital images, and were through to be analogous to the wind ripples that we see on the slopes of terrestrial dunes (e.g., Sullivan et al., 2008). However these large ripples have very different morphology and dynamics (Silvestro et al., 2016) and in fact are superimposed by small ripples (∼10 s cm wavelength) that have morphology more similar to terrestrial impact ripples (but were not visible within orbital images; Fig. 10). The large ripples are now hypothesized to be fluid-drag ripples (Bagnold, 1941; Wilson, 1972), which on Earth form under water, but on Mars are able to develop sub-aerially because of the higher kinematic viscosity of the low density atmosphere (Lapotre et al., 2016a). This example shows the limitations of analysis from a spatially and temporally limited dataset and interpretation from a limited perspective (e.g., only orbital imagery), even when we think that we understand what we are looking at. Additionally, the limits of comparative planetology can mean we misinterpret observations where we lack a terrestrial analog.
- Dune sand grain sizes on Mars have been estimated since dunes were first seen, based on assumptions about conditions for dune formation (Phases 1 & 2). Efforts to "measure" grain sizes from proxy thermal inertia estimates have also been undertaken (mentioned within Phase 4), and compared to and debated against the assumptions about the ability of the wind to move grains of different sizes. Studies based on these estimations, and their results, now should be re-evaluated as the MSL Curiosity rover has recently completed the first in situ investigation of a dune located on a planet other than Earth (Phase 7), yielding the first direct measurements of martian dune grain sizes (Fig. 11). While on Titan sand grain sizes have not yet been measured in situ (and won't be in the near-future), studies have explored what grain sizes can be reached via feasible physical processes which puts constraints on models of dune formation conditions, and visa-versa.

Additionally, it is important to recognize the gaps and limitations that can occur in aeolian studies if only the "standard" aeolian science inputs are considered (e.g., the "complementary sciences" listed in Table 1 also need to be considered). As in all areas of planetary science and geology, it is important to consider many pieces of information (and observations, as possible), and all need to be consistent with the model for the model to be validated. For example, while potential sediment sources can possibly be tracked from visible imagery, climate models, and/or topography models, compositional information about the dune grains and the potential sand sources is needed to check that the model is consistent with the full environment. This may extend beyond compositional information in the local environment (which was included in Phase 2), as grains may have been transported over large distances or have been recycled a few times – and this history may not be apparent without a broad-swath of environmental information. Additionally, processes outside of standard, dune-forming aeolian processes may be playing a role in dune evolution and observed morphology. For example, the dunes in the martian polar regions have morphologies and features different from those in the equatorial region, making it clear that polar processes are altering the aeolian bedforms and thus must be considered in their interpretation (e.g., in the north: Hansen et al., 2011, 2015; in the south: Fenton and Hayward, 2010).

3.2. Connections to modeling of the physical processes

As discussed above, looking at aeolian bedforms on other planets allows models to be tested against a range of environmental and planetary conditions. From that, we refine our understanding of aeolian processes without assumption of Earth-conditions. This can especially have a large impact on models of the small-scale and complicated dynamics of sand-wind and sand-sand interactions. For example, as discussed under Phases 2 and 6, our understanding of the way in which sand is picked up by the wind, causing or continuing saltation, has now been "tested" under terrestrial, martian, and venusian conditions (Kok, 2010; Kok et al., 2012), resulting in an updated model of how saltation and reptation are initiated and interact.

On Titan, questions about how "sticky" organic sand particles would interact with the wind were part of an investigation to explain how the dunes had formed, and from that to connect the crestline orientation to the forming-wind direction(s). The Titan dune sand color appears consistent with a composition of organics, and such long-chain molecules (of as-yet undetermined exact composition) could be derived from the atmospheric photodissociation of methane, which creates small particles (Carl Sagan's "tholins") that snow down from the atmosphere (and then perhaps get incorporated into surface sedimentary layers or clump together into larger granules, that are eroded and transported to the dune-forming regions) (Radebaugh, 2013; Barnes et al., 2015). Studies of clay-rich dunes in China had revealed that "sticky" particles could form dunes, but would anchor themselves to the downwind edge of a longitudinal dune and thus grow and migrate the dune along the dune crestline; this was proposed as a potential analog to the Titan dunes (Rubin and Hesp, 2009). Although the Titan dune morphologies were overall found to be more consistent with freely-moving particles (i.e., the saltation usually observed on Earth), and thus this longitudinal dune formation model is less favored than the model discussed in Subsection 2.2, this type of questioning highlighted a different type of terrestrial dune-formation mechanism and "tested" behavior of the traditional dune formation model if one does not assume a non-cohesive sand grain. This led to further development of a dune-wind alignment model that brought these two hypotheses together as well as explained how bedforms with different alignments can exist within the same multidirectional wind regime (Courrech du Pont et al., 2014). Within this single model, dune alignment reflects growth via either a "bed instability mode" (which approximates the longitudinal dune growth process proposed by Rubin and Hunter (1987) and Rubin and Ikeda (1990)) or a "fingering mode" (the growth process proposed by Rubin and Hesp (2009)), depending on sediment availability.

Models that examine larger-scale dynamics can also be tested through application to different planetary surfaces. For example, it was in studying martian dunes that a discrepancy was noticed between the minimum dune size expected on that planet (∼100× the minimum Earth dune size) and that observed (∼10×), thus driving new models of dune formation to explain the scaling factor. Model studies aiming to replicate the observed minimum barchan dune size on Earth and Mars addressed this question, and tested assumptions about how saltation, reptation, and wind drag interact in setting characteristic sand trajectory distances, and from this the generation of instability within a sand bed under a shearing fluid (Claudin and Andreotti, 2006).

3.3. Connections to terrestrial studies and knowledge gain

The trajectory of terrestrial dune studies has differed markedly from the framework proposed here for planetary dune studies. In essence, the difference is one of top-down vs. bottom-up approaches as in situ observations of terrestrial landforms, conditions, and activity are significantly easier to carry out. However, this has not resulted in the history of terrestrial dune fields being an opposite to the sequence suggested as being characteristic of planetary dune research. The earliest published studies of terrestrial dune fields were linked with exploration by non-indigenous people, and many of the founding points of contemporary dune science can be traced to these expeditions. The exploration of the southern African and Australian interior (mid-19th century), the Sahara (around the beginning of the 20th century, mostly by the French in the west and the English in the east) and the Arabian Rub al'Khali (most notably by Wilfred Thesiger in the late 1940s) all had exploration as their primary goals. As with contemporary rover exploration of the martian dune fields, many dune fields were approached with trepidation due to the hazards they posed. Despite science being incidental rather than implicit to most of the explorations, there was, nonetheless, early recognition of the great spatial extent of many dune fields, the remarkably organized nature of dunes, and the fact that dunes could exist at differing activity levels.

Although Bagnold's work in the 1930s and 1940s is most commonly cited as being the foundation of modern understanding of aeolian processes and landforms, there were significant precursors. George Perkins Marsh (1965) considered geoengineering problems associated with drifting sand, and the role of vegetation in stabilizing dunes, and Russian geologist Nikolay Sokolów had discussed dune sedimentology and theories of dune formation in a 300-page book devoted to the subject (1894). Georges Rolland, a French mining engineer, set out a series of propositions in 1890 based on fieldwork in the Algerian Sahara which addressed such issues as sediment source, the distribution of dune fields, varying levels of dune activity, and the relationship between wind regime and different dune shapes (Burt et al., 2008). At this point, the role of the wind in dune formation was still contested by many, and it was widely held that dunes would prove to have rocky cores (Goudie, 2002). Many other aspects of contemporary aeolian science date from surprisingly early studies. Aerial imagery was used to examine dune planform morphology in the 1930s (Aufrère, 1932; Madigan, 1936), and the recognition of dunes as a particulate waveform in a fluid medium can be traced to the work of Cornish (1914). Bagnold's work, utilizing field and wind tunnel experimentation, is an early example of the 'quantitative revolution' widely recognized in geosciences in the middle of the 20th century. This directly influenced the next half-century of research, via fieldwork and laboratory experimentation, in a phase perhaps best summarized by Lancaster's (1995) state-of-the-art textbook. Coincidentally, the same year saw the publication of Werner's (1995) application of cellular automata models to aeolian bedforms, which accepted that dunes formed as an emergent property of a complex system, one of the first indications of the failure of reductionist approaches to fully explain aeolian landscapes (Livingstone et al., 2007). The same period saw the rise of the use of luminescence dating to provide ages for dune emplacement, since described as having has a transformative effect on studies of dryland science (Singhvi and Porat, 2008).

Planetary studies of aeolian dunes therefore have the advantage of decades of terrestrial work to draw upon, and this is reflected in the very rapid progress made on newly-discovered dunes (e.g. Titan, Comet 67P). Terrestrial science, conversely, has had the advantage of a relatively steady progression in the quality and quantity of the available data – although the related understanding of aeolian systems has not progressed as steadily. The progress made in understanding terrestrial dunes has not been without challenges, and it is instructive to reflect on whether there are lessons for the planetary community can be drawn from progress on terrestrial dune fields, and conversely whether the evolution of extraterrestrial dune research can inform the research strategies of Earth's dune studies.

3.3.1. What can planetary science learn from the history of terrestrial dune studies?

Much of planetary dune science is already directly influenced by the methods, theory and process understanding derived from terrestrial studies, manifest in the numerous analog studies. However, there are some less well-discussed points that are worthy of consideration.

As was noted in Section 3.1, close attention must be paid to the difference between assumed and observed knowledge. Cautionary tales can be drawn from terrestrial dune studies, and this is perhaps best illustrated by the roll vortex hypothesis for longitudinal (linear) dune formation. First proposed by Bagnold (1953), and promoted subsequently (e.g. Hanna, 1969) this suggested that thermally induced vortices in regional wind-flow would lead to the development of helical horizontal flow cells that might lead to sand accumulation in linear bedforms extending downwind. The theory is strikingly devoid of empirical supporting evidence, and yet still persists in the literature. Quite simply, vortices of sizes that might explain dune spacing have never been observed despite numerous experimental attempts, and the transverse component of roll vortices does not appear to have sufficient velocity to move sand (Lancaster, 1995). Planetary studies should be careful to question existing paradigms and theories, and be willing to point out when data do not support these hypotheses.

Bagnold's great advances in aeolian science can be largely attributed to willingness and fearlessness towards innovation, in terms of methods and physical exploration. The novel application of wind tunnels to aeolian transport and sedimentation and the methods developed to enable remote desert travel directly enabled the advances in understanding that Bagnold brought. Planetary perspectives support this, with the radical advances in data brought from missions such as MSL, Cassini/Huygens, Rosetta/Philae and New Horizons. Such evidence supports the potential knowledge gains from similarly ambitious mission concepts of other planetary surface exploration missions, such as the proposed Aerial Vehicle for In situ and Airborne Titan Reconnaissance (AVIATR) mission (Barnes et al., 2012) and the Venus In Situ Explorer (VISE) mission (NRC, 2013). The evidence from both terrestrial and planetary dune studies suggests that high-risk, innovative research has led to some of the greatest advances.

The discrepancy between the timescales of aeolian process and the timescales evident in aeolian landscapes is also very evident – possibly even more so – on some planetary bodies. Despite processes operating within dune landscape on timescales of seconds to hours, the resultant landscape development frequently operates on timescales of $>10^3$ years. Dating of aeolian sediment, primarily via the suite of luminescence dating methods, has been adopted very widely on terrestrial dune studies, and has played a crucial role in linking the short-term processes with the long-term geomorphological record. It has enabled calculation of rates of landform evolution beyond that possible using observational records (e.g., Kocurek et al., 2007; Telfer, 2011), revealed complex spatial variability in aeolian accumulation (Telfer and Thomas, 2007) and frequently been used to infer external drivers of dune activity (e.g. climatic changes). Experimentation with luminescence readers suitable for Mars missions has been explored (e.g. McKeever et al., 2003; Jain et al., 2006), and if the substantial technical challenges can be overcome (Doran et al., 2004), martian luminescence dating offers the potential to extend understanding of accumulation beyond the period of direct observation. Recent progress suggests that solutions may exist to these challenges (e.g. Sohbati et al., 2012).

3.3.2. What can terrestrial dune studies learn from the history of planetary science?

Although at least parts of Phases 1–3 and 5–7 have been investigated on Earth for 70 years or more, a striking difference between planetary and terrestrial dune studies is that currently there is no global catalogue of dunes for Earth (Phase 4). Early global maps of aeolian features were studied within a decade of the start of relevant data collection (Thomas, 1982), the first edition of the Mars Global Digital Dune Database (Hayward et al., 2007) was published within six years of the start of the Thermal Emission Imaging System (THEMIS) data collection (Christensen et al., 2004) (which has been used to identify the thermal inertia proxy identifiers for dune fields (Christensen, 1983)), and global mapping of Titan's dunes within the constraints of the available data (Lorenz and Radebaugh, 2009) was published within a similar timeframe since the arrival of Cassini at Titan. Although some terrestrial regions have been mapped and duneforms catalogued (e.g., Namib; Livingstone et al., 2010), and a global database of dunes with dating constraints has recently been complied (Lancaster et al., in press), global-scale consideration of terrestrial dune fields is lagging behind planetary science. Efforts in this direction are currently in progress (Hesse et al., 2015) – but it has been over 40 years since the advent of global terrestrial satellite coverage. The focus of planetary global catalogues of dunes has been on understanding global circulation patterns (e.g. Charnay et al., 2015; Ewing et al., 2015), sediment sources (e.g. Tirsch et al., 2011), identification of large-scale variations in dune form due to different evolution processes or rates (e.g., Fenton and Hayward, 2010; Savage et al., 2014), and targeting areas for detailed study (e.g., Hayward, 2011). While it is not necessary to use dune morphology to understand modern circulation patterns on Earth, applications of such a database would include quantification of aeolian sediment volumes and flux, improved understanding of regions where dunes are currently stabilized, and potential for monitoring change in environmentally-sensitive, dynamic landscapes.

Livingstone et al. (2007), reviewing the state of understanding of terrestrial dune geomorphology, concluded that decades of largely inductive, and increasingly reductionist, study had not brought the completeness of understanding that had been hoped, and that integration of methodologies (field, modeling and remote sensing) offered the best prospects for knowledge. Perhaps due to the difficulties in conducting 'field study' of extraterrestrial dunes (i.e., Phase 7), which are only very recently being overcome on Mars, such combined strategies are often exemplified by planetary aeolian studies, where studies employing a wide range of methodologies including numerical modeling, laboratory experimentation, field study (mostly via analog environments), and remote sensing are commonplace (e.g., Lucas et al., 2014). Although some terrestrial studies do synthesize such diverse methodologies, the example set by many planetary studies is a good one for terrestrial dune studies.

Much of the focus of this paper has been on the increasing availability, resolution, and coverage of new remotely sensed data. The same has been true for Earth, and here lessons learned in planetary studies help guide interpretation of terrestrial images at the margins of the spectral and/or spatial resolution of the imagery. This is perhaps best illustrated with the example of the highly contested issue of extensive palaeo-dune fields in the Amazon Basin, presently covered with extensive tropical forest. Tricart (1974), working with recently-released first-generation Landsat imagery, identified widespread stabilized aeolian landforms in the tropical Amazon Basin. This interpretation was repeated numerous times (e.g. Klammer, 1982) and lead to a widespread belief in arid phases accompanied by vegetation loss during the late Quaternary evolution of the region, with huge implications for understanding of regional biogeography in one of the world's most biodiverse regions. However, while subsequent reanalysis of high-resolution data has revealed aeolian dune fields around the margins of the Amazon basin (e.g. Teeuw and Rhodes, 2004; May, 2013) and/or immediately adjacent to large rivers where the sediment supply has at times been the dominant control (e.g. Carneiro Filho et al., 2002), the existence of wide swathes of paleodunes across the Amazon basin has not withstood closer scrutiny (Colinvaux et al., 2001). Tripaldi and Zárate (in press) reviewed the evidence, and demonstrated the importance of groundtruthing when image interpretation is challenging. Planetary geomorphologists are usually admirably conservative in terms of implying process from (apparent) landform, especially when imagery is at the limit of its spatial or spectral resolution, and terrestrial incidents such as the question of an arid Amazon suggest that such conservatism is wise.

4. Conclusion/summary

Studies of aeolian bedforms over a wide range of planetary bodies have resulted in significant progress in our understanding of past and present climate and surface conditions, physical processes, and the interconnectivity of dynamics over a range of spatial and temporal scales. These studies contribute, in meaningful and often unique ways, towards a range of planetary science investigations. For example, as discussed, interpretation of dune morphology often provides unique, if proxy, groundtruth data about past or present wind conditions, and the proven presence of a large amount of sand grains can drive investigations about processes responsible for creating such grains. Beyond studies that involve this type of direct interpretation of the aeolian bedforms, aeolian science studies also yield information about many tangentially-related areas of investigation. In particular, aeolian-driven sand flux appears to be an important force in erosional modification of a planetary surface. Quantitative estimations of wind speeds and sand flux and identification of sediment transport pathways yield quantitative estimates of erosional process rates. This can, for example, lead to improved interpretation of observed landforms – such as yardangs (e.g., Ward, 1979), or the rate of crater degradation by aeolian processes which is important for accurately estimating the age of a planetary surface (e.g., Golombek et al., 2014; Grant et al., 2006, 2008, 2016). This can also provide bounds on surface-ages of exposed rock surfaces, which is can be of importance to rover missions – such as Mars missions searching for accessible environments near the surface that may have been habitable and that may include preserved biosignatures (e.g., Arvidson et al., 2015).

As discussed, planetary aeolian studies have also made key contributions towards improving the methodologies employed in aeolian science, and in challenging assumptions built (perhaps inadvertently) into aeolian process models based on terrestrial observations. To-date, this has resulted in the refinement of several models of dune-field forming processes, from interactions between sand grains and the wind or with each other, up through interactions between dunes and topography and climate shifts.

Given all of the ways in which our aeolian study results impact our understanding of planetary surface conditions and histories (as well as the Earth's), it is thus very important to critically look at how we progress in planetary aeolian science, and in particular to consider carefully which results (and resultant models) are based on assumptions versus observations – and then to revisit those results when new information becomes available. Here, we have proposed one framework for identifying progress within planetary aeolian studies, and have used that framework to chart the progression of data, assumptions, and generated knowledge. We hope this framework, and our identification of gaps, will help future planetary aeolian researchers strategically fill knowledge gaps or at least carefully recognize where assumptions are being used to progress a study.

Additionally, this framework may help identify the types of data that would be most useful for future planetary missions. Pluto, Io, and Comet 67P were all discussed as having reached Phase 1, where at least a potential aeolian bedform has been observed. On Titan, global datasets exist and have contributed to large shifts in our understanding of the Titan climate and organic cycles. Venus also has a global topography dataset, but the low resolution and apparent lack of dune fields stalled progress in its aeolian science investigations (and thus related advancements in planetary surface studies). Unfortunately for Venus and Titan, further progression within Phases 2–4 (and movement into Phases 5 and beyond) will likely need to wait for new and higher-resolution surface datasets.

Mars' aeolian bedforms are the best studied within planetary aeolian science (outside of Earth's), with both widespread coverage in certain data-types and many regions with high-resolution data regarding the dunes' and dune field environment's morphology and composition, collected over the past 43 years. However, with the progress that has been made, we cannot lose sight of the fact that much of it has been built on interpretations of remote data. (As discussed under Phase 7, in situ dune field observations have not been possible until just recently.) Furthermore, much of the work involves a meshing of coarse global data with a few more-deeply monitored and studied dune fields, and thus much extrapolation is done that assumes certain types of consistency between fields. This is an odd contrast with Earth dune field studies, where the global dataset (Phase 4) is what is missing.

For all planetary bodies (including Earth), we look forward to further advancements in the interpretation of aeolian bedforms and what interpretations about those bedforms will imply about the environmental conditions and processes. If history is to be any guide, with each advance into a new phase (due to acquisition of a new type of data and/or enablement of a new type of analysis), we find exciting new understandings about that planetary body and the general understanding of aeolian processes. One area of intriguing advancement is the prediction of where dunes and/or ripples could be found (which could be thought of as a "Phase 0" within our framework). As we explore more bodies and learn more about the conditions under which bedforms resembling aeolian dunes are found, we can wonder about the next place where we may expect to find dunes, as well as identify lessons to aid in such predictions (e.g., when we return to Venus). In addition, perhaps in the near future, we will move into a yet-undefined Phase 8 (e.g., through comparison between in situ measurements of some very different types of aeolian bedforms? Hints of that are starting with sand grain comparisons (e.g., O'Connell-Cooper, 2016)), yielding a new type of data that can supersede assumptions made in Phases 1–7, further expanding our broad understanding of aeolian processes and bedforms, and increasing the overall information gained from planetary aeolian studies.

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